PB-240 963

ENFORCEMENT ECONOMICS IN AIR POLLUTION CONTROL

Paul B. Downing, et al

Washington Environmental Research Center
Washington, D. C.

December 1973

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BIBLIOGRAPHIC DATA SHEET

1. Report No. EPA-600/5-73-014

2.

PB 240 963

4. Title and Subtitle
"Enforcement Economics in Air Pollution Control"

5. Report Date
December 1973

6.

7. Author(s)
Paul B. Downing and William D. Watson, Jr.

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Washington Environmental Research Center
Implementation Research Division
Environmental Protection Agency
Washington, DC 20460

10. Project/Task/Work Unit No.
1HA094

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
(same as 9.)

13. Type of Report & Period Covered
Final Report

14.

15. Supplementary Notes

16. Abstracts

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In a simulation of current enforcement of the federal new source particulate matter discharge standard for coal-fired power plants it is found that cost-minimizing power plants will install relatively costly pollution control technology and frequently violate federal fly ash standards. Two alternative enforcement strategies for overcoming these shortcomines, namely compliance tests in combination with emission taxes and emission taxes alone, are analyzed.

In the case of the federal fly ash discharge standard for coal-fired power plants it is tentatively concluded that emission tax enforcement would probably result in an approximate minimization of the sum of firm and enforcement agency resource costs. The general applicability of this result to other enforcement problems is discussed.

17. Key Words and Document Analysis. 17a. Descriptors

Economic Analysis
Policy Tradeoffs
Pollution Control
Enforcement Policy
Cost-Effectiveness
Monte Carlo Simulation

17b. Identifiers/Open-Ended Terms

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US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

17c. COSATI Field/Group 0503

18. Availability Statement
Release Unlimited

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages
113

22. Price
$5.25/2.25

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EPA-600/5-73-014
December 1973

ENFORCEMENT ECONOMICS IN AIR POLLUTION CONTROL

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Program Element 1HA094

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ABSTRACT

This report investigates the effects of alternative enforcement strategies on the pollution control activities of the firm. There are a number of tradeoffs available to a firm including delay and non-compliance which allow it to minimize expected pollution control costs. These are identified within the context of a generalized behavioral model for the firm and an empirical study is undertaken to determine their importance.

In a simulation of current enforcement of the federal new source particulate matter discharge standard for coal-fired power plants (start-up compliance or certification tests for pollution control devices plus fines for violating in-operation emission standards) it is found that cost-minimizing power plants will install relatively costly pollution control technology and frequently violate federal fly ash standards. Two alternative enforcement strategies for overcoming these shortcomings, namely compliance tests in combination with emission taxes and emission taxes alone, are analyzed.

It is recommended that enforcement agencies give careful consideration to management costs imposed upon the firm and the control agency by an implementation and enforcement scheme. In the case of the federal fly ash discharge standard for coal-fired power plants it is tentatively concluded that emission tax enforcement would probably result in an approximate minimization of the sum of firm and enforcement agency resource costs. The general applicability of this result to other enforcement problems is discussed.

CONTENTS

Page

Abstract ii

List of Figures iv

List of Tables v

Preface vi

Sections

I Summary, Recommendations, and Conclusions 1

II Optimal Control 10

III An Enforcement Model of the Firm's Control Behavior 16

IV A Simulation of Enforcement Alternatives 29

V Policy Analysis 57

VI Policy Recommendations 70

VII Interpreting the Results 78

Footnotes 82

References 85

Mathematical Appendix 87

FIGURES

No.		Page
1	Standards Enforcement	12
2	Distribution of Measurement Errors for Two Alternative Emission Monitors	24
3	Alternative Forms of Penalties for Air Pollution Violations	27
4	Precipitator Operating Curves	33
5	Simulation Model, Scenarios S1-S4	35
6	Fines and Emission Taxes	38
7	Compliance Test Tradeoffs	40
8	Simulation Model, Scenarios S5 and S6	43
9	Fines and Control Effort	54
10	Cost Comparisons	58
11	Enforcement by Compliance Test and Opacity Standard, 1300 Megawatt Plant	61
12	Enforcement by Compliance Test and Emission Tax, 1300 Megawatt Plant	64
13	Technology-Cost Tradeoffs (Current Enforcement Practice)	67
14	Control Effort (Current Enforcement Practice)	71
15	Effective Legal Enforcement	74
16	Effective Emission Tax Enforcement	76
A.1	Beta Distribution Shapes Programmed in Monte Carlo Model	91

TABLES

No.		Page
1	Regression Coefficients from Simulation Analyses, S1: Compliance Test with Fine for Violating an Opacity Standard (Inflexible Technology)	47
2	Regression Coefficients from Simulation Analyses, S2: Compliance Test with Fine for Violating an Opacity Standard (Flexible Technology)	48
3	Regression Coefficients from Simulation Analyses, S3: Compliance Test with Tax on Emitted Fly Ash (Inflexible Technology)	49
4	Regression Coefficients from Simulation Analyses, S4: Compliance Test with Tax on Emitted Fly Ash (Flexible Technology)	50
5	Regression Coefficients from Simulation Analyses, S5 and S6: Emission Tax Only	51
6	Current Enforcement Practice	56
A.1	Nonmenclature	92-94
A.2	Electrostatic Precipitation Parameters	95
A.3	Compliance Test Failure Probabilities (R = 1.15V, Compliance Test Standard = .04)	96
A.4	Compliance Test Failure Probabilities (R = 1.1V, Compliance Test Standard = .04)	97
A.5	Compliance Test Failure Probabilities (R = 1.15V, Compliance Test Standard = .1)	98
A.6	Compliance Test Failure Probabilities (R = 1.1V, Compliance Test Standard = .1)	99
A.7	Precipitator Characteristics (Inflexible Technology)	100
A.8	Precipitator Characteristics (Flexible Technology)	101
A.9	Characteristic of Cost Parameter Distributions	102
A.10	Fixed "Costing" Parameters	103
A.11	Representative Flue Gas Volumes and Precipitator Sectionalization for Different Sized Power Plants	104

PREFACE

This report is part of the Implementation Research Division's (IRD) research program on the implementation aspects of environmental pollution control. As a part of this program, the Division is engaged in comprehensive studies of the economics of pollution control regulatory activities. A major goal of these studies is to provide information on and insights into the economic aspects of determining environmental standards and pollution control strategies.

The body of information presented in this report is directed to those individuals concerned with efficient and cost-effective enforcement of environmental standards. Its aim is twofold. One is to determine some of the differing impacts upon firm behavior of legal enforcement, of economic incentive enforcement, and of mixed legal-economic enforcement. A second objective is to initiate identification of enforcement systems which are most likely to minimize resource costs to firms and enforcement agencies of meeting environmental standards.

Several other IRD studies deal with related subjects. They include "An Economic Analysis of Periodic Vehicle Inspection Programs" by Paul B. Downing (Atmospheric Environment, Dec. 1973), "A Cost Evaluation of Alternative Air Quality Control Strategies" by Donald H. Lewis and Scott E. Atkinson (forthcoming) and "Costs and Benefits of Fly Ash Control" by William D. Watson, Jr. (Journal of Economics and Business, May 1974).

The authors are grateful to their colleagues in IRD for many helpful comments at various stages of this research. The study has benefited substantially from their suggestions.

Alan Carlin
Director, IRD

SECTION I

SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

Current pollution control efforts are directed mainly at establishing environmental standards which protect human health and welfare. This is a fundamental step toward improving environmental quality and it is not surprising that a great deal of attention is presently focused on this activity. One must be careful, however, not to overlook important interfaces or couplings in this endeavor. For example, it is very important to anticipate reactions both to environmental standards and the methods used to enforce them. Indeed, in this report we show that standards setting cannot be divorced from enforcement. Several examples suffice to illustrate the linkages. For instance, a standard--whether it be tight or lax--which is not enforced may lead to excessive pollution damages to human health and welfare. On the other hand, heavy handed enforcement may lead to very high enforcement costs which may also reduce human welfare because large amounts of resources would be devoted to enforcement at the expense of attractive alternative employments. In actual fact, the situation may be somewhat more complicated than this since complex feedbacks may induce counterproductive behavior. A very strict standard may lead a control agency to engage in vigorous enforcement. But the firm being regulated may resist via legal maneuverings simply because this is less costly than controlling pollution. This in turn could lead the control agency and firm to engage in further legal battles, all of which results in spiralling enforcement costs but little pollution control.

Our objective in this report has been to theoretically and empirically model firm and pollution control agency pollution control behavior in sufficient detail so that we can determine enforcement policies which minimize the total resource costs (insofar as they can be measured) of meeting environmental standards. Resource costs are defined to include out-of-pocket pollution control costs to the firm (such as the capital and operating costs of pollution control equipment), firm management costs (such as the costs of monitoring discharges and conducting start-up compliance tests for pollution control devices), pollution control agency enforcement costs (such as the costs of inspection and preparing legal suits against firms accused of violating standards), and the damage costs of residual or after-control pollution. We do consider other firm costs such as fines and emission charges but since these are transfer costs and not resource costs they are excluded in identifying enforcement policies which minimize resource costs. The analysis has both a static and dynamic dimension. The static analysis investigates enforcement responses given current technology; the dynamic analysis attempts to determine the type of enforcement policies which provide incentives to firms to develop and adopt resource efficient pollution control technology over time.

It is assumed throughout that firms are primarily motivated by the desire to minimize their expected costs, or obversely for fixed prices and outputs, to maximize their expected profits. In the theoretical sections of this report we comprehensively cover possible reactions to pollution control enforcement including such alternatives as "public relations" on the part of both firms and enforcement agencies. In response to enforcement policies, firms actually have a wide variety of alternative reactions. These can range all the way from complete compliance to delay and non-compliance wherein firms legally challenge enforcement and use public relations to advertise "their side of the story". Our analysis assumes firms will weigh the costs of each of these actions and choose the least costly alternatives. For their part, enforcement agencies also have similar choices. For instance they may choose to publicly disclose uncooperative and recalcitrant behavior on the part of non-complying firms. It is, of course, in the interest of firms to anticipate this and to act accordingly. Our theoretical analysis allows tradeoffs along these lines. The empirical part of this report, however, is constrained by data availabilities. Here we undertake a much less ambituous analysis of enforcement behavior. We investigate responses of regulated firms only; enforcement agency behavior is not modeled due to lack of data. Furthermore, this empirical analysis does not allow for subtle variations such as those produced by public relations efforts. Nonetheless our empirical analysis does produce a variety of interesting and useful policy implications and we do point out the sensitivity of our conclusions to missing links.

The empirical section considers three alternative enforcement policies. One, termed current enforcement practice because it is modeled after enforcement guidelines promulgated by EPA, uses start-up compliance or certification tests for pollution control devices and fines for violating in-operation emission standards. A second enforcement policy which we consider uses compliance tests in combination with per unit taxes (emission or effluent taxes or fees) on discharged pollutants. A third policy is emission taxes alone. Allowance is made in the analysis for firm influence on compliance test conditions and on fines and probabilities of conviction when emission standards are violated.

It is useful to differentiate the two different but related optimizing orientations covered by the analysis in this report. One is that of economic efficiency. The other is cost-effectiveness. An economically efficient pollution control level and enforcement policy is identified as a level of pollution control and an enforcement policy for which marginal resource costs of control equal marginal benefits and for which total net benefits are maximized. This is also equivalent to a policy which minimizes total resource costs when resource costs are defined comprehensively, that is, when they include internal resource costs to firms and enforcement agencies and total external damage costs of discharged pollutants. In a norrower framework where marginal benefits or pollution damage costs are not known it is not possible to determine efficient policies; consequently, in such cases the analysis focuses on cost-effective policies which are defined as enforcement policies which minimize the internal resource costs (i.e., excluding external pollution damage costs) of meeting any given environmental standard. Our theoretical analysis focuses on both efficient and cost-effective enforcement policies while our empirical analysis focuses mainly on cost-effective policies.

There are two basic messages of our analysis. One is that there are many alternatives for setting and enforcing a pollution control standard. These can range from systems which rely mainly upon legal sanctions to systems which rely totally upon economic incentives. In any event it is probably desirable to identify and implement efficient policies if that is possible, and if not (say due to lack of data on pollution control benefits) then an attempt should be made to identify and implement cost-effective policies, that is, enforcement policies which minimize the sum of resource costs to firms and enforcement agencies of meeting any given environmental standard. Our analysis provides guidelines for implementing efficient and cost-effective policies. A second message, especially relevant for control of stationary source pollution, is that current enforcement practice is probably not cost-effective. In this report we identify several alternative methods of enforcement which would probably substantially reduce internal pollution control resource costs below the levels achievable under current enforcement practice.

The following specific conclusions and recommendations have emerged from our work:

-- The optimal level of control of emissions depends upon the cost of the control devices or process changes, the management costs imposed on the firm by the control agency, and the management cost of the control agency itself (and, of course, the benefits of control). These costs are likely to differ among alternative implementation and enforcement schemes. In order to determine the optimal implementation and enforcement scheme it is necessary to determine the optimal control level, and hence values of policy parameters, for each alternative. The net benefit of control for each alternative could then be compared and the scheme with the largest net benefit chosen. While we cannot prove it without further research, the evidence we present indicates that an effluent fee enforcement scheme would be optimal in controlling fly ash emissions from coal-fired power plants. However, we do not expect this result to apply universally to other situations. Some form of legal enforcement may be preferred in many cases. This is especially true in cases where continuous monitoring of emissions is technically difficult and expensive.

-- Our analysis indicates that when information and management costs are included the optimal effluent fee system consists of a marginal charge and a lump sum charge. The marginal charge would be set equal to the firm's marginal control cost, including its internal management costs, at the point where the optimal control would be obtained. The fee is less than marginal benefits at the optimal control level. The lump sum charge would be based upon the control agency's management costs. Not including the lump sum allows firms to bear less than the full social cost of control thus leading to inefficiently large output of final goods and pollution.

-- Assuming that firms are expected cost minimizers we find that different implementation and enforcement techniques imply different reactions to control agency policy. Under a legal enforcement system the relevant policy parameters are inspection and monitoring techniques, emission standards, device certification procedures, probability of conviction if accused of a violation, fines and shutdown penalties, and damage to the corporate image. As one would expect there are tradeoffs among these policy parameters. For example, in our simulation of fly ash control we find that stricter compliance tests (a certification of a control device) and less stringent opacity (emission) standards can yield the same level of control. The model indicates that a higher marginal fine or penalty would yield greater control. In our emprirical case, however, we find that any positive effective fine will have the same effect on the firm's control decision. This probably is not a general result.

In effluent fee enforcement the relevant policy parameters are the marginal fee, the device certification process if any, and the inspection and monitoring system employed. As expected, higher effluent fees yield greater control. When a certification procedure is added to the effluent fee we find that a tradeoff between the certification standard and the effluent fee exists. This is born out in our empirical test. However, there is a range of effluent fees for which any feasible compliance test will have no effect on the firm's control efforts.

-- We find that very high accuracies in monitoring devices are not needed to determine compliance with some desired pollution control standard. All that is necessary is a monitor which has a known relationship between what it measures and the pollutant to be controlled and a known measurement error. Thus, efforts should be directed toward developing monitoring systems for difficult to measure emissions rather than improving the accuracy of already adequate monitors.

With an adequate monitoring device, the control agency can adjust the emission standard or fee to fully account for measurement errors. The confidence level at which they decide that a violation has occurred is a function of the costs of making Type I and Type II errors. The higher the cost of not stopping violators in terms of damages from pollution, the lower the confidence level (or higher the probability of incorrect accusations) the control agency should pick.

-- Our analysis shows that when a plant fails a compliance test, an enforcement agency must be willing at all times to say to the operator of that plant: "You cannot open your plant." Without this threat firms will install and operate grossly inadequate pollution control devices especially under enforcement via start-up compliance tests of control devices and fines for violating in-operation emission standards (current enforcement practice), less so under enforcement via compliance tests combined with per unit emission taxes.

-- Under current enforcement practice, the threat of almost any positive effective fine when the emission standard is violated is a necessary condition for enforcement success. Positive effective fines encourage firms to maintain their pollution control equipment.

-- Under enforcement schemes using compliance tests, our analysis indicates that plants, especially large ones, will vigorously seek relaxations in the conditions under which compliance tests are conducted. The reason is that low compliance test flue gas flow rates, and small numbers of averaged compliance tests, and large numbers of successive re-runs of the compliance test reduce fail probabilities, making "shoddy" devices with their smaller costs, least costly. Obviously, an enforcement agency in seeking effective compliance should attempt to prevent such relaxations. Unfortunately, federally promulgated guidelines already permit as few as three averaged stack samples during compliance tests for fly ash control and an unlimited number of successive compliance tests.

-- Under current enforcement practice, most coal-fired power plants will not meet federal new source fly ash standards. Since our analysis is not unusual in any way, we suspect that this non-compliance result also applies to some degree to similar enforcement practices for other pollution standards.

-- Under current enforcement practice, small power plants in comparison with large plants will control at higher levels which is inefficient. This is likely to hold generally for any enforcement systems which use compliance tests and fines for violating in-operation emission standards.

-- Current enforcement practice for pollution control is likely to lead to some reductions in pollution, but it does this with a rather severe dynamic penalty. Our analysis indicates that such enforcement will probably lead to the selection of inflexible technology and to negative economic incentives towards the development and adoption of more flexible and consequently less polluting abatement technologies including process modification. By 1980, extra stationary source pollution control resource costs for the U.S. stemming from mis-directed technology selection under current enforcement practice are likely, at the very least, to be running at the rate of $75 to $150 million per year. There is the further danger under current enforcement practice (no emission taxes) that damages are going to be suboptimally high because firms will not be paying the full social costs of their emissions. Without emission taxes, firms may produce more that the optimal level of output and emissions.

-- Compliance tests with emission taxes or emission taxes only are two alternative enforcement policies which would overcome most of the deficiencies of current enforcement practice. While it will not be universally the case that legal or current enforcement practice is less preferable, we feel that in a high percentage of the cases it will be inferior to effluent fee enforcement.

-- Effluent fee enforcement provides incentives toward the adoption of efficient technology. Furthermore, since effluent charges are immediate there is little the firm can do to avoid compliance. There is, however, one sense in which firms could avoid or delay compliance under effluent tax enforcement. This is by initial challenges to effluent tax legislation. Our simulation results indicate that effective emission tax enforcement of new source federal fly ash standards for coal-fired power plants can raise costs by as much as 25% above costs incurred under current enforcement practice. This means, of course, that there are substantial cost saving payoffs to firms from preventing effluent tax enforcement of pollution standards. The message for pollution control agencies is that substantial legal resources may have to be devoted to an initial legal defense of effluent tax legislation.

-- Once the initial challenge to effluent tax enforcement has been met, there is likely to be substantial enforcement cost savings to those pollution control agencies using effluent tax enforcement of pollution standards. Right away, compliance tests and the costs of policing them can be eliminated. There is also almost no need to retain a staff of enforcement agency lawyers who periodically threaten to prosecute violating firms under the civil suit provisions of the Clean Air Act, the effluent charge itself now more effectively plays this role. Firms also have less incentive to retain lawyers for purposes of delaying enforcement; effluent charges provide immediate incentives towards control and consequently firms would tend to shift resources away from delaying and non-compliance tactics towards pollution control activities. Policing of stack monitoring is the one activity to which a pollution control agency must devote substantial resources under effluent tax enforcement. Cost minimizing firms will achieve high collection levels only if full and proper effluent charges are levied. Honest and hence carefully policed stack monitoring is a necessary condition for effluent fee enforcement.

SECTION II

OPTIMAL CONTROL

Overview. The use of the environment by a firm can impose uncompensated costs on other firms or on individuals. There are two general methods which may be employed to internalize these costs to the polluting firm; namely, emission standards and emission charges.[1] In assessing the cost of pollution control typical studies look only at the cost of the control device or process change without concern for the institutional constraints placed on the firm by the control agency and the legislature. Yet it is clear that the firm incurs differential expenses in addition to (or instead of) the actual installation and operation costs of the control device or process change itself. These additional expenses can include compliance testing or other certification expenses, legal expenses, fines, and other enforcement costs. These expenses are a function of the implementation and enforcement rules employed by the control agency. Hence they are likely to vary with the method of internalization (policy instrument) chosen.

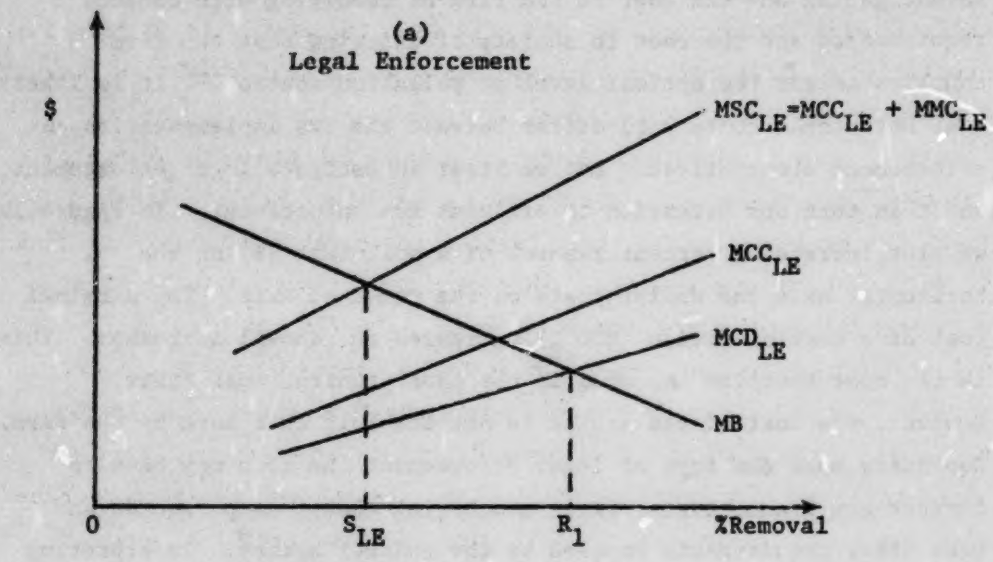
The goal of this paper is to determine the likely effect on a firm's control actions of alternative implementation and enforcement policies available to the control agency. Three alternatives are studied, legal enforcement through the new source performance standards set forth by EPA and two effluent fee enforcement alternatives. First, a generalized model of the effects of implementation and enforcement policies on the firm's control actions is developed. This model assumes that the firm is an expected cost minimizer. The model is then applied to the case of particulate matter discharges from coal-fired power plants in order to estimate empirically the effect of policy alternatives on the firm's control efforts. Finally, the results of the model and its empirical application are used to develop policy functions which relate control to the values of various policy parameters. These results lead us to several policy recommendations.

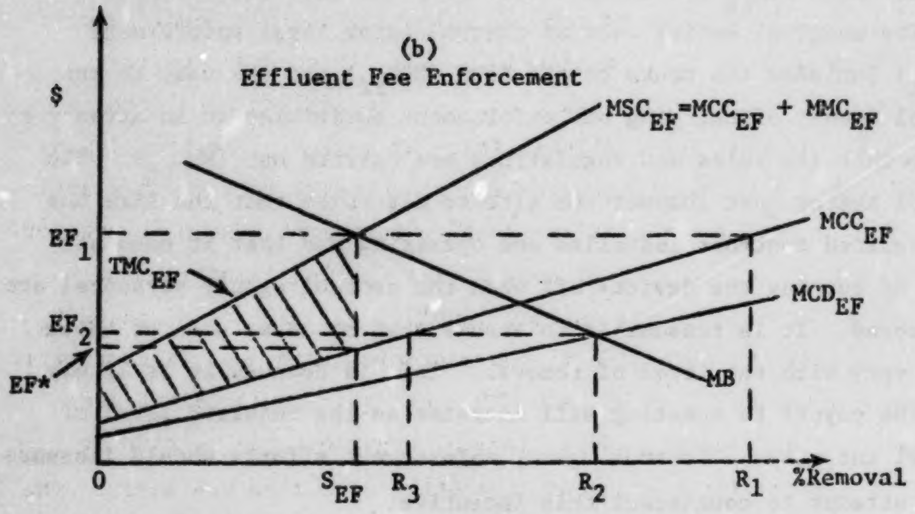
Optimal Emission Standards and Taxes. Before we proceed with the development of our model, a general framework is provided by investigating how the cost to the firm of complying with control requirements and the cost to society of insuring that the firm complies affect the optimal level of pollution control.[2] It is likely that both these costs will differ between the two implementation and enforcement alternatives. Let us first investigate legal enforcement and then turn our attention to effluent fee enforcement. In Figure 1a we plot increasing percent removal of a pollutant (R) on the horizontal axis and dollar costs on the vertical axis. The marginal cost of a control device (MCD_{LE}) increases as removal increases. This is the cost function measured in the usual control cost study. However, the cost of the device is not the full cost born by the firm. Depending upon the form of legal enforcement the firm may have to conduct compliance tests, incur monitoring costs, keep records and meet other requirements imposed by the control agency. Interpreting these curves as planning horizon cost curves it is clear that at least some of these compliance costs vary with R. Thus the marginal cost of control for legal enforcement (MCC_{LE}) which the firm actually faces includes both MCD_{LE} and these other costs and lies above MCD_{LE}.

The marginal social cost of control using legal enforcement (MSC_{LE}) includes the costs to the firm (MCC_{LE}) and the cost to the control agency of carrying out enforcement activities in an attempt to insure that its rules and regulations are carried out (MMC_{LE}). The control agency must inspect the site to determine that the firm has the required controls installed and operating and that it does not cheat by turning the devices off when the control agency personnel are not around. It is reasonable to assume that at least some of these costs vary with the level of removal. This is because it is likely that the payoff to cheating will increase as the required level of control increases. Control agency enforcement efforts should increase in an attempt to counteract this incentive.

Assuming the usual declining marginal benefit function (MB), the

Figure 1
Standards Enforcement


(a)
Legal Enforcement


(b)
Effluent Fee Enforcement

optimal level of control would be where MSC_{LE} = MB or S_{LE} in Figure 1a. Note that when it is recognized that social control costs are greater than the cost of the device itself, the optimal level of control of pollution is less than that usually determined in empirical studies (R_1). The neglect of these costs would lead to the setting of a standard which is inefficiently stringent.

In Figure 1b the same conceptual set of functions is presented for the effluent fee enforcement case. However, each of these functions may differ from their legal enforcement equivalents in their actual location on the graph. There are compliance costs for the effluent fee enforcement system as well. The firm must record emissions, pay the fee, deal with periodic checks by control agency personnel, etc. It is reasonable to assume that these compliance costs would increase with the level of removal. Likewise, the marginal management costs to the control agency are likely to increase with the level of removal. This is because higher removal and consequently greater effluent fees makes cheating more profitable to the firm. This in turn necessitates greater checking by the control agency. The optimal control level is at S_{EF} where MSC_{EF} = MB (which does not change with the enforcement technique employed).

If society's goal is to control pollution at least cost (and if it wished to neglect distributional issues), it should pick that institutional form which is least costly. Economists have often argued that the best institutional form for pollution control is the effluent fee. For this to be true it is necessary that the net social benefit of control for the effluent fee enforcement system is greater than the net social benefit of control for the legal enforcement system where each is at its optimal level (i.e., MSC_{LE} = MB and MSC_{EF} = MB). In order to determine if the economists argument is correct it is necessary to know both MCC and MMC under legal enforcement and effluent fee enforcement. While logical arguments can be made to support the economist's argument, the other side also has merit. The determination will probably rest on empirical evidence yet to our knowledge no such estimates exist. This paper attempts to fill part of this gap by determining the firm's cost functions under alternative enforcement policies. The determination of the control agency's cost functions are left for further determination.

If it is truly the case that effluent fee enforcement systems are preferable, one might ask why government continues to employ legal enforcement methods. There are several possible explanations. In many cases measurement of effluent quantity is technologically difficult and expensive. This certainly can explain why some emissions are not controlled through effluent fee enforcement. But there are other cases where the measurement problem is not severe. There is another possible explanation for avoiding effluent fees. The effluent fee system implies that property rights to the air are vested with the general public. Thus, the firm must pay not only cleanup costs but also a sum for residual damages (the effluent fee). This makes the firm's out-of-pocket costs higher for effluent fee enforcement than for legal enforcement thus reducing the profitability of the firm and the wealth of its owners. Furthermore, the effluent fee system places the burden of control technology research and development on the firm while legal enforcement places the burden of proof and hence research and development responsibility on the control agency. Shifting to an effluent fee system would increase the firm's research and development outlays and further reduce the owner's wealth (in some transition period). There are obvious incentives for firm owners to opt in favor of legal enforcement if they are forced to control.

The government bureaucracy also prefers the legal enforcement system. This is because it gives them substantial power in the control decisions of the firm. Also, because they must demonstrate the availability of technology, their budgets are large compared to budgets under an effluent fee system. Legal enforcement may also require a larger enforcement staff. Bureaucrats prefer systems which increase their power, staff, and money because these lead directly to greater prestige and remuneration.

Before we turn to the model and the empirical analysis one additional point needs to be made. The economic literature agures that an effluent fee be set at the point where MSC = MB (EF_1 in Figure 1b). This is incorrect since the firm will equate the fee to MCC_{EF} and overcontrol at R_1. Empirical studies of cost functions imply that the effluent fee should be set at EF_2 where MCD_{EF} = MB and predict a suboptimally high control level at R_2. This also is incorrect since the firm will actually control at R_3 which may be greater or less than S_{EF} depending upon the costs of implementation and enforcement to the firm and to the control agency. The optimal effluent fee is at EF* since at this point the firm will control at S_{EF} where EF* = MCC_{EF}. Note that at this point the effluent fee is less than MB by the cost of implementation and enforcement to the control agency (MMC_{EF}). This level of fee provides the correct marginal signals to the firm but it does not provide the correct total conditions. In addition to the effluent fee it is necessary to collect an amount equal to the total management costs imposed on the control agency by the firm (TMC_{EF}) in a lump sum. This will cause the firm to include the total costs it imposes on society from using the environment. In a perfectly competitive world, not paying this full cost would cause an inoptimally large output for the industry and allow submarginal firms to continue operation. In the non-perfectly competitive world the lump sum payment may cause a suboptimally small output.[3/]

To summarize, we find that the firm reacts to a marginal cost function which includes both the costs of control and implementation and enforcement imposed upon it. These costs as well as the costs of implementation and enforcement to the control agency differ for various institutional forms of control. The preferred institutional form is the one which maximizes the net social benefit of control. The optimal effluent fee system is a combination of a marginal effluent fee equal to MCC_{EF} at the removal rate where MSC_{EF} = MB and a fixed fee equal to the total annual management costs (TMC_{EF}) imposed on the control agency by the firm.[4/]

SECTION III

AN ENFORCEMENT MODEL OF THE FIRM'S CONTROL BEHAVIOR

This section derives a model of the firm's reactions to enforcement strategies. It then explores various cases to determine the likely reaction of the firm to alternative values of the policy variables under differing technological and time frame assumptions. In the following section this model is applied to the case of new source performance standards for fly ash discharge from coal-fired power plants.

Becker (1968) developed a model of the economics of crime and punishment which consists of damages function, an enforcement cost function, a supply of offenses function, and a punishment function. Interpreting his results in terms of the air pollution control problem we address in this paper, his damages function is the dollar value of the damages dones to society when emissions from a source exceed a given standard (thus constituting an offense). The corresponding punishment function reflects this dollar damage and the cost of enforcement function.[5/] This procedure is conceptually similar to pollution control through the institution of an effluent charge system but it differs in two significant ways. First the offense system is a threshold system which presumes that in the absense of an offense there are zero dollar damages from pollution. It postulates a threshold to pollution damages while the effluent charge system generally assumes the more likely case of a continuous damage function. Since there are probably residual damages incurred at an optimally set standard, the threshold concept can lead to an inefficient solution. Second, the fine Becker suggests would include both the damages and the cost of enforcement born by society. The second part of this fine generally is not considered in setting effluent fees, hence making such fees inefficient.

Becker's supply of offenses function can also be interpreted in terms of air pollution control. The polluter's supply of offenses (the number of times he exceeds the standard) are assumed by Becker to be a function of the probability of his being convicted, the fine he pays per conviction, and what Becker calls "a portmanteau variable" representing the sum of all other influences. It is this supply of offenses (emissions) function that we explore for the air pollution case in this paper. Specifically stated, our goal is to investigate the reactions of an individual firm to alternative standards, conviction probabilities, and fines (the policy variables) under different implementation schemes.

Costs of Pollution Control to the Firm. It is assumed for the purposes of this paper that the firm seeks to minimize the expected cost of control of pollutants [E(CC)].[6/] These expected costs are the sum of the expected cost of control devices [E(CD)] and the expected cost of compliance and enforcement actions imposed on the firm for compliance or non-compliance with required controls or standards [E(EC)]. The firm's objective function[7/] is then

$$(1) \qquad \min E(CC) = E(CD) + E(EC)$$

given a fixed set of control regulations (the policy variables). Both CD and EC are stochastic in this formulation. Device costs include both capital and installation costs (KC) and operation and maintenance costs (OM). For many devices OM will have some distribution about an expected value because the device might partially or fully fail during the period (as when a catalytic reactor gets poisoned). Enforcement costs are stochastic because the control efficiency of the device is stochastic causing the incidence of violation to be uncertain. A complete analysis of E(CD) is not necessary for our purposes. It is assumed here (and later shown for the electrostatic precipitator case we explore empirically) that:

$$\partial E(CD)/\partial R > 0$$

and

$$\partial^2 E(CD)/\partial R > 0$$

The arguments in the E(EC) function are somewhat different depending upon the implementation and enforcement method used. For the legal enforcement method now employed for new sources by EPA the expected enforcement and compliance costs are a function of the expected number of days the firm is detected to be in non-compliance during the year [E(N)] times the expected penalty imposed on the firm for each violation [E(P)].

$$(2) \quad E(EC) = f[E(N) \cdot E(P)]$$

E(N) is a function of the expected control efficiency of the device installed by the firm [E(R)] given the various rules and regulations imposed upon the firm by the control agency and/or the legislature.

$$(3) \quad E(N) = g[E(R) \mid I, S, C]$$

where

I = the frequency, accuracy, and form of the inspection and monitoring actions of the control agency

S = the emission standard set by the control agency

C = the requirements set by the control agency for certification of the effectiveness of the firm's control device (usually through some sort of compliance testing procedure).

That is, for any given set of control agency policies, the higher E(R) the lower E(N). If the control agency were to increase its enforcement efforts by increasing the frequency of inspections, improving the accuracy of monitoring, or making compliance tests more strict, any given E(R) would imply a larger E(N). Likewise, a more stringent emission standard would increase E(N).

The expected penalty is a function of the probability of being convicted of being in violation (PC), the money fine imposed on the firm by the courts if convicted of being a polluter (F), the damages to the firm's image if convicted (DI) and the possible shutdown time (ST) for required repairs or construction if found in violation by either the control agency or the courts.

$$(4) \quad E(P) = h(PC, F, DI, ST)$$

PC is a function of the legal costs incurred by the firm to defend itself against the control agency (LC). The effectiveness of a dollar spent on defense depends upon the control agency's prosecution efforts (CAP).

$$(5) \qquad PC = k(LC|CAP)$$

The firm will minimize its cost where:

$$(6) \qquad \partial E(CC)/\partial R = \partial E(CD)/\partial R + \partial E(EC)/\partial R = 0$$

Since enforcement costs decline as removal increases, this condition can be satisfied. For a set of policy parameter values equation 6 defines the values of MCC_{LE} and MCD_{LE} as equal to the values of $\partial E(CC)/\partial R$ and $\partial E(CD)/\partial R$ respectively.

In the case of pure effluent fee enforcement the E(EC) function is less complex. Expected enforcement costs are simply a function of R and the level of the effluent fee (EF) per unit of emissions given some monitoring and inspection system and possibly some certification of the control device as well.

$$(7) \qquad E(EC) = m(R,EF|I,C)$$

where

$$\partial E(EC)/\partial R < 0$$

and

$$\partial E(EC)/\partial EF > 0$$

Alternative Enforcement Strategies. Having discussed the factors which affect the firm's expected cost of environmental control, we turn our attention to the effects of alternative enforcement strategies on this expected cost and the firm's reaction in terms of pollution control.

Let us assume that the control agency has an air quality goal which it is attempting to reach using the legal enforcement method. It has several policy tools available by which it can effect the control efforts of the firm. It can set higher or lower emission standards, change penalties for non-compliance, make court actions more prompt, and impose external pressures on the firm through public statements.

Standard. Local air pollution control agencies are faced with the problem of obtaining control efforts by firms and individuals sufficient to reach specified air quality goals. They may recognize that control devices do not work perfectly all the time. Thus, in order to insure the desired level of total emission control the agency could set individual standards at a higher level than would be required if all devices worked perfectly.

The firm will react to the higher standards by installing more effective devices but only under specified conditions. The firm will control to the desired level only if the expected penalties and court costs are higher than the cost of control. It will delay as long as the court cost of delaying actions is less than the interest on the cost of control devices and savings in operation and maintenance expenses. As we will see below, the savings in O&M expenses may drop out if enforcement after installation of the device is lax. This implies that lax enforcement can increase initial compliance by the firm but this may not yield a net improvement in emissions.

The above argument implies that enforcement is the key to compliance with an emission standard. However, for a given enforcement cost to the firm, a higher standard will cause the firm to attempt more delaying actions. This is because a higher standard implies higher control costs to the firm thus making court actions more cost-saving.

Monitoring. The lack of any monitoring of the control actions of the firm will make any standard set by the control agency ineffective. It is obvious that if E(EC) is zero the firm will minimize costs by not controlling. And E(EC) will be zero in the absence of a monitoring effort. The frequency and type of monitoring will also affect the firm's compliance.

There are two stages of our legal enforcement model. One for the situation before the firm takes any control action and another for the situation after the installation of control equipment. This is because control and enforcement costs differ in the two cases. To make this distinction clear, equation (1) is rewritten as follows.

$$(8) \qquad \min E(CC) = KC + E(EC_B) + E(OM) + E(EC_A)$$

where:

$E(EC_B)$ = expected enforcement cost before installation of a control device.

$E(EC_A)$ = expected enforcement cost after installation of a control device (i.e. during operation).

In the before installation case all of equation (8) holds although it is possible that $E(EC_A)$ may be zero in which case the last two terms will drop out. If the control agency were to step up its before installation monitoring (increase I_B), the firm would find it more expensive to delay compliance. However, this result holds only if the penalty increases with the number of times the firm is found not to have installed the required devices. Since this is not usually the case, one inspection to determine non-compliance is sufficient until the firm claims compliance.

After installation of the required devices the first two terms on the right hand side of equation (8) drop out. The firm is faced with the choice of operating the device or not and its decision clearly depends upon $E(EC_A)$. This in turn depends upon I_A. Assuming that each violation detected by an inspection is a separate offense (the usual case in control legislation), an increase in I_A will *cet. par.* yield more control. The device will be operated more effectively and more often. But the form as well as the frequency of inspection will affect this result.

Inspections might be announced ahead of time (either formally or through indirect means) or they could be unannounced. The cost-minimizing firm facing announced inspections will operate the device during the inspection only if the penalty for non-compliance is greater than the O&M costs. After the inspection $I_A = 0$ and thus $E(EC) = 0$. This being the case the firm will not operate the device until the next announced inspection. Indeed it has been observed that when control authority personnel go home at night firms take the opportunity to blow the accumulated fly ash out of the stack. This can be safely done because, in effect, the control agency has announced non-inspection.

If inspection is unannounced, the firm will operate and maintain the device as long as $E(OM) < E(EC_A)$. Thus, increased frequency of inspection cet. par. will cause more effective operation of devices and more emission control.

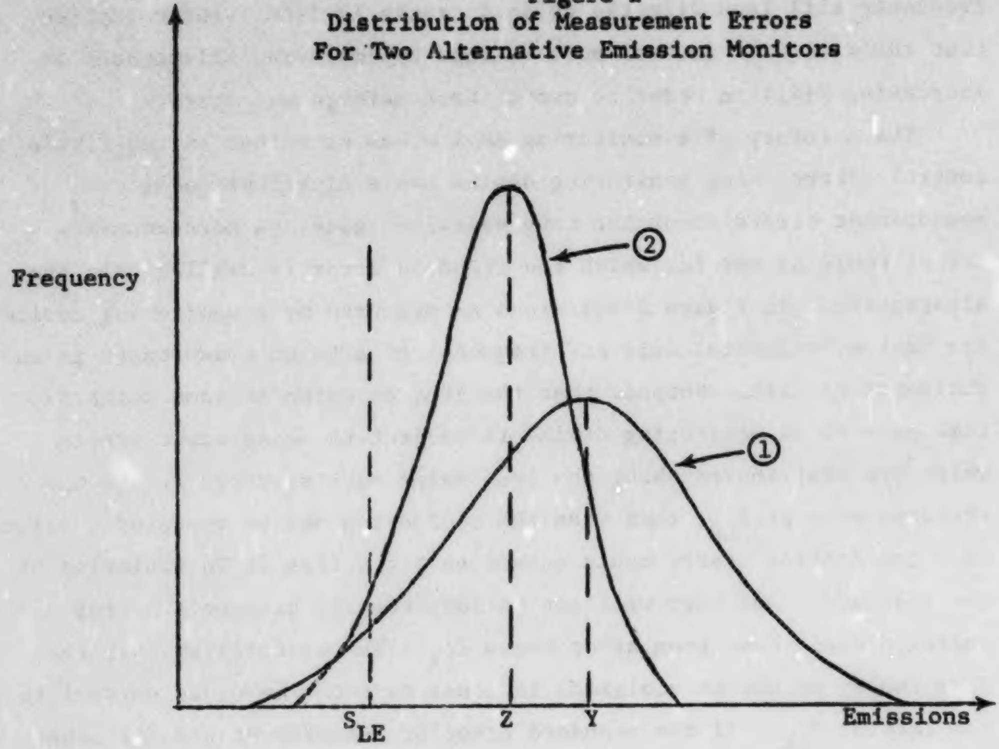
Another policy choice available to the control agency is inspection to determine the actual emissions of the firm rather than inspection to determine if devices installed are in good operating condition (no obvious malfunctions). The control efficiency of any given device depends upon certain design parameters, some random performance, and the chance that the device will partially or fully fail to function. If inspection measures actual emissions, the full model applies. The firm will operate and maintain the device being conscious of the actual effectiveness of the device as long as the savings in enforcement costs justify operation. Also, when faced with this sort of inspection the firm may find it advantageous to install a device with a larger E(R) than otherwise required. The larger E(R) will reduce E(N) thus making violations less frequent. The firm will incur additional installation and associated O&M costs to the point where the cost of increasing E(R) (marginal cost) equals the savings in enforcement costs.

A variant of this case is currently being used by EPA in its new source performance standards. In this case a compliance test is required which samples the actual emissions during the test period to determine if the device will control emissions to the required level. After the device passes the compliance test and the plant is opened, a continuous monitor is employed to insure that the device is in operation and that it is not suffering from a serious malfunction.

It is obvious that the frequency of monitoring will affect control efforts of the firm. The more frequent I_A the greater $E(EC_A)$. This is because each violation constitutes a separate offense. For example, if the probability that the observed removal rate is less than the standard equals 10 percent and this probability is constant over time, then the firm will expect to be found in violation once if inspected ten times and ten times if inspected one hundred times or 10 percent of the time if continuously monitored. Thus, the number of accusations, given some set of design parameters and O&M efforts, is solely dependent on the frequency of inspection. An increase in this frequency will lead directly to an increase in $E(EC_A)$ which implies that the firm will control more (either by improving maintenance or increasing $E(R)$) in order to avoid these enforcement costs.

The accuracy of a monitoring device has no effect on the firm's control effort. Any monitoring device has a distribution of measurement errors about the true emission value. A more accurate device would be one for which the standard error is smaller than the alternative. In Figure 2 emissions as measured by a monitoring device are on the horizontal axis and frequency of a given measurement is on the vertical axis. Suppose that the true emission at some point in time were Y. A monitoring device is subject to measurement errors which are distributed about the true value such as curve 1. If the standard were at S_{LE}, then when the monitoring device measured a value of Y the control agency could assume that the firm is in violation of the standard. But they will not be 100% certain because the true emission could have been at or below S_{LE}. The probability that the firm really is not in violation is equal to the area under curve 1 to the left of S_{LE}. If the standard error of measurement and the shape of the distribution are known this probability can be calculated. Alternatively stated, if the control agency observes a reading of Y, it can be X% confident that the firm is in violation (X given by the area under curve 1 to the right of S_{LE}). Curve 2 in Figure 2 represents a more accurate monitoring device (one with a lower standard error of measurement). At some reading from device 2 closer to S_{LE} (Z, for example) the control agency can also be X% confident that the firm is in violation. Thus the control agency can choose a

Figure 2
Distribution of Measurement Errors
For Two Alternative Emission Monitors



confidence level it wishes and determine the monitor reading which corresponds to this level of confidence given the measurement error of the monitor. Any reading equal to or greater than this point, which we will call S_{LEA}, will be presumed by the control agency to show that the firm is in violation. A more accurate device would result in a S_{LEA} that is closer to S_{LE} but if the confidence level remains constant, then it has no effect on E(N). The effective policy parameter is the confidence level chosen by the control agency. The higher the confidence the control agency chooses, the fewer will be the citations for a violation given a level of E(R). However, as the confidence level increases the control agency is more likely to win in court if the firm contests a citation. Thus, a higher confidence level will cause PC to increase and E(N) to decline. The net result on the firm's control actions depends upon its relative cost of control on the one hand and court action and fines on the other.

The problem for the control agency of correctly setting S_{LEA} merits more discussion. Increasing the confidence level required before a citation is issued means that firms which are in violation will be cited less frequently. This error is costly because true violations supposedly cause damages. At the same time, higher confidence levels imply reduced probabilities that a firm which is not in violation will be incorrectly cited. This type of error is also costly since the control agency must use its scarce resources to prepare and prosecute the case. If it looses the case, it will have wasted its resources (and those of the firm and the court). If it wins, the firm may be forced to control to an inefficiently high level. Thus, there is a tradeoff available between Type I and Type II errors. The control agency will maximize at that confidence level where the marginal costs of making Type I and Type II errors are equal. If pollution damages are rapidly increasing with emissions above the standard, the optimal confidence level will result in a relatively large number of incorrect citations. On the other hand, if the economic (and political) costs of issuing many incorrect citations is high, high confidence levels will be chosen. As we will see below, current control agency policy tends toward this case.

It could often happen that the control agency is faced with a S_{LEA} which is set by statute and would require long delays to change. If the control agency wishes to increase its confidence level in these circumstances, it could require a more accurate device be used in monitoring.

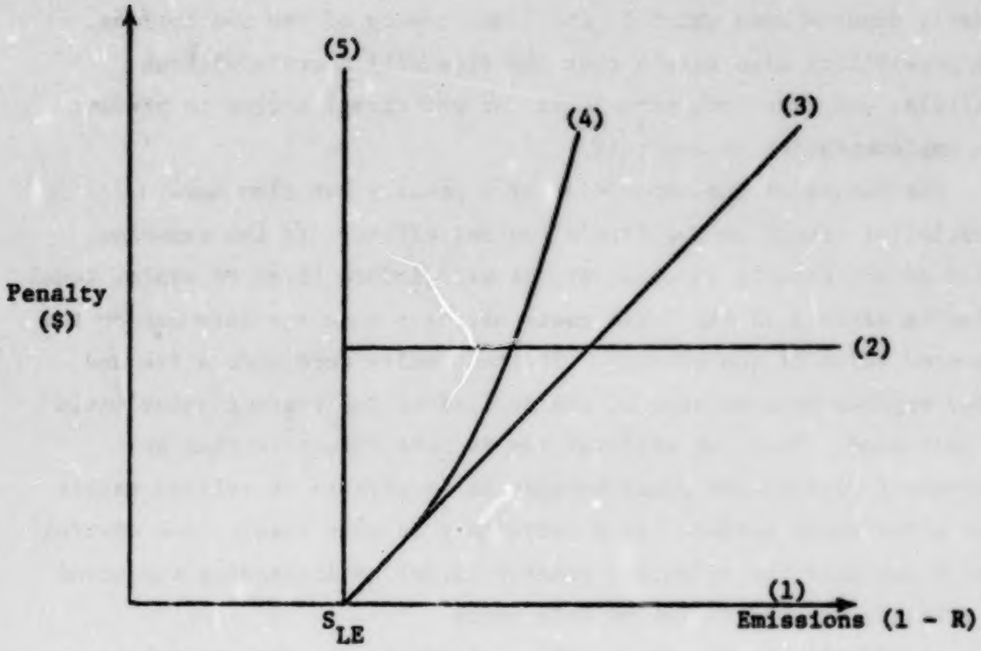
Penalty. It is perhaps obvious that increasing the level of penalty imposed will increase compliance by the firm. There are, however, some circumstances under which this will not occur. If there were no inspection then any level of penalty will have no effect. It could also be the case that it is less expensive to incur court costs to fight the penalty than to increase control. This might be the case either with high or low penalties. In the very high penalty situation, the firm may feel that it has a good chance of getting the court to rule that the penalty is excessive.

The form of the penalty can also have an effect on the firm's control efforts.[8] The form of penalty imposed can be classified into the following groups: (1) cease and desist orders, (2) constant penalty per violation, (3) constant penalty per pound of pollutant released above the standard, (4) increasing penalty with the number of pounds of pollutant released above the standard, (5) a shutdown order. These alternatives are depicted in Figure 3. S_{LE} is the firm's standard and emissions increase as you move to the right.

Cease and desist orders have no immediate effect because they impose no penalty at that instant. However, if they imply a larger penalty for future violations they may induce additional control in the future. The constant penalty per violation is an all or nothing case. Since the penalty is independent of the size of the violation, the firm will spend less to reduce major breakdowns than might be optimal relative to minor violations, where the device is removing almost all the pollutants required, considering that breakdowns are probably more damaging to society.[9] The use of the constant or

Figure 3

Alternative Forms of Penalties for Air Pollution Violations



increasing charge per pound reduces this effect. Now, since the penalty for a complete breakdown will be substantially higher than for a minor violation the firm will spend more effort on reducing breakdowns. More reliable devices will be sought. However, since minor violations are relatively less expensive, this reduces the incentive to install devices with $E(R)>S_{LE}$. The non-linear form makes breakdown prevention relatively more important to the firm. The penalty in the shutdown order case is the loss in profit to the firm due to not operating. Whether the firm closes down or controls clearly depends upon which is the least costly of the two options. The possibility also exists that the firm will operate without controls, and take long term legal (or political) action to prevent the implementation of controls.

The timing of the imposition of a penalty can also have a substantial effect on the firm's control effort. If the expected value of the penalty is constant, it will induce firms to employ legal delaying actions if the legal costs are less than the interest on the expected value of the penalty. If the penalty were made a fee and hence payable upon release of the pollution, its present value would be increased. Thus, an effluent tax is more effective than an equivalent penalty per pound because it is payable on release rather than after court action. As a corrollary to this result, the control agency can make the effective penalty larger by increasing the speed of bringing accused violators into court.

In addition to the above policy alternatives, the control agency has two more options. First, it can try to obtain more tightly written laws which would increase the probability of obtaining a conviction (make the penalty more certain) and/or improve their preparation to the same end.[10] Second, the control agency can increase the damage to the firm's image by publicly announcing violations.[11]

In this part of the paper we have identified conceptually the tradeoffs available to the firm under alternative policies of the control agency. In the following sections we attempt to assess empirically the magnitude of these tradeoffs.

SECTION IV

A SIMULATION OF ENFORCEMENT ALTERNATIVES

In the preceding section of this paper we have presented a general theory of a firm's reactions to environmental control implementation and enforcement alternatives. In order to demonstrate some of these propositions and determine their empirical significance a simulation study was conducted for enforcing the federal new source performance standards for particulate matter discharges from coal-fired power plants. The simulation model employed allows us to determine the likely control actions of the firm (and related costs) resulting from alternative levels of enforcement policy parameters and implementation schemes. In effect, via this analysis we will be examining a variety of enforcement "experiments".

Ideally it is desirable to find the set of enforcement policy parameters which minimize the sum of resource costs for both firms and enforcement agencies. This analysis, however, covers only costs to firms since data and information on enforcement agency costs are almost nonexistant. Nonetheless it will be seen that the partial results reported here are rich in policy implications.

It is assumed throughout that managers of coal-fired power plants attempt to minimize expected costs over their planning horizons and that available cost effective fly ash control technology is electrostatic precipitation (see Watson (1974)). We deliberately focus upon interpretations of the model, its results and related policy issues. Mathematical details of the model can be found in an attached appendix.

In this section we begin with a discussion of the new source performance standards for fly ash control. Next we present a diagrammatic exposition of the simulation model. The results of the simulation analysis are then compiled. Policy analysis and recommendations based on these results are presented in a following section. A final section of this report discusses the impact on the analysis of some of the key assumptions which underlie our simulation model; this final section also discusses application of the results of this analysis to other pollution control problems.

New Source Performance Standards. Final rules and regulations for particulate matter discharges from fossil-fueled steam generators were issued by the U.S. Environmental Protection Agency on December 23, 1971 (Federal Register December 23, 1971 pp. 24876-24895). Particulate matter discharges (which are mainly fly ash and unburned carbon particles) are not to exceed 0.1 lb. per million B.t.u. heat input maximum 2-hour average. This standard is applicable to any power plant unit of more than 250 million B.t.u. per hour heat input or approximately 25 megawatts in capacity whose construction is commenced after August 17, 1971. Eventually, with the retirement of pre-standard plants, every plant will be subject to the standard.

Under these regulations, firms are required to pass compliance tests on fly ash control devices before new plants go into operation. A plant is certified for operation when, on the basis of prescribed stack testing procedures, discharges during the test period are no greater than the standard. During operation, opacity of stack discharges is to be continuously monitored by the firm at its expense and reported to EPA. If the firm violates the opacity standard (20 percent opacity) it can be charged in a civil action under the provisions of the Clean Air Act and if convicted, fined as much as $50,000 per day of violation.

These regulations have several peculiar features. For one thing, the start-up compliance test can be run an unlimited number of times. Secondly, the conditions under which compliance tests are to be conducted are not clearly defined:

> All performance tests shall be conducted while the affected facility is operating at or above the maximum steam production rate at which such facility will be operated and while fuels or combinations of fuels representative of normal operation are being burned and under such other relevant conditions as the

> Administrator (of EPA) shall specify based on representative performance of the affected facility. (Ibid. p. 24879.)

Beyond these general stipulations, the rules and regulations do not specify test conditions. Presumably EPA technical personnel will be on hand to check test conditions. The tests, themselves, will be conducted by utility company personnel. A strong fraternity of engineering interests is likely to pervade compliance testing activities with liberal interpretations of test conditions "being understood" by the participants. A third feature is that the average of as few as three compliance test stack samples is the measurement for comparison with the promulgated standard:

> Each performance test shall consist of (at least) three repetitions of the applicable test method. For the purpose of determining compliance with an applicable standard of performance, the average of results of all repetitions shall apply. (Ibid. p. 24878.)

As will be seen, the number of successive compliance tests, the stringency of test conditions, and the number of averaged compliance test stack samples markedly influence firm behavior.

A peculiar feature of the federally promulgated opacity standard, the basis for detecting a violation during operation, is that it allows roughly twice the quantity of discharges as are allowed by the particulate matter discharge standard. This too influences firm pollution control effort.

The Simulation Model. We have simulated six policy scenarios:

	Inflexible Technology	Flexible Technology
Compliance Test with Fine for Violating an Opacity Standard	S1	S2
Compliance Test with Tax on Emitted Fly Ash	S3	S4

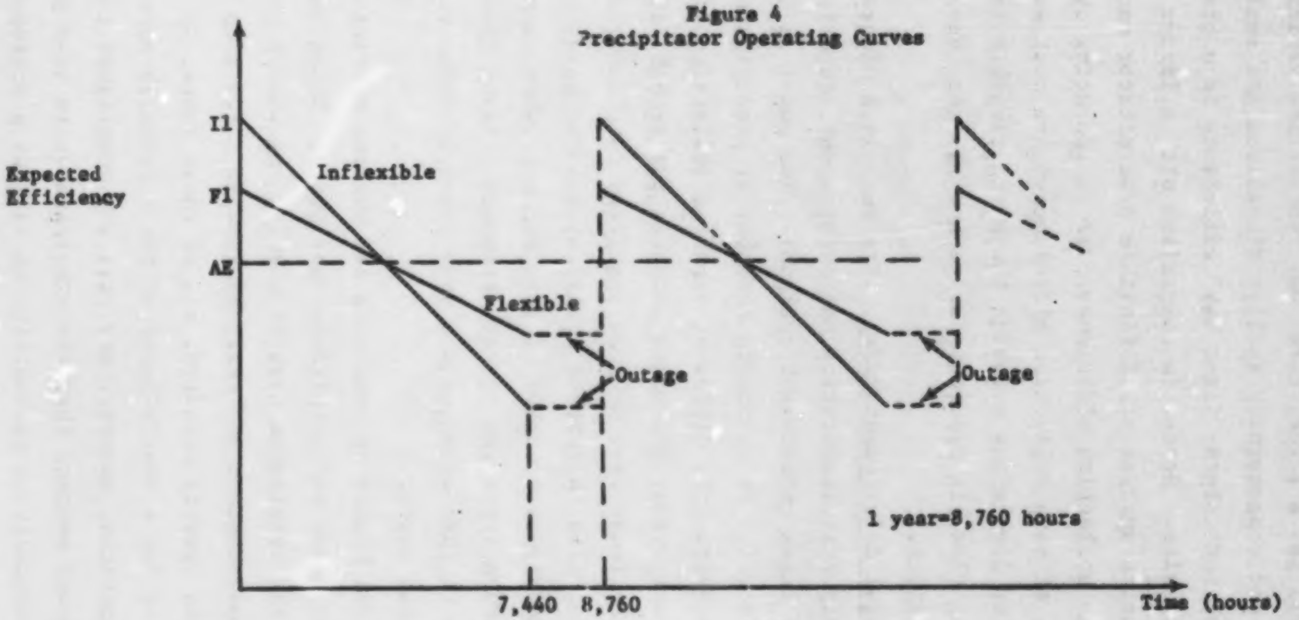
Emission Tax Only	S5	S6

Our model describes the firm's least-cost effort to control fly ash discharges given each of the three enforcement policy sets listed above and two variants of electrostatic precipitator technology: inflexible and flexible.

Figure 4 demonstrates the difference between flexible and inflexible precipitator technology. Expected collection efficiency is measured on the vertical axis; operating hours are measured on the horizontal axis. A typical base loaded power plant will operate about 7440 hours per year, the remaining hours in that year will be outage hours when normal maintenance is performed on generating equipment and pollution control devices. The two curves labelled "inflexible" and "flexible" show that precipitator efficiency declines over operating hours. This occurs because precipitator discharge electrodes fail, lowering the filtering capacity of the precipitator (Greco and Wynot (1971)). It is plausibly assumed that the failure rate is negative exponential which produces an approximately linear (in efficiency) operating curve for precipitator performance. The dashed-line sections of the operating curves represent precipitator maintenance time during scheduled outages of the power plant. On restart, precipitators again perform at top efficiency. This cycle of deterioration, maintenance, and re-start at top efficiency produces the ratcheted performance curves of Figure 4. By comparing the two performance curves it is seen that a flexible precipitator's efficiency declines less rapidly during an operating cycle. This results from having power shunting electronic instrumentation which optimizes precipitator filtering capacity as discharge electrodes fail.

As drawn in Figure 4, the flexilbe and inflexible operating curves produce the same average efficiency (AE) over the operating cycle. The curves have purposely been drawn in this way to illustrate the fact that a flexilbe precipitator (for the same over-the-operating-cycle average efficiency relative to an inflexible

Figure 4
Precipitator Operating Curves



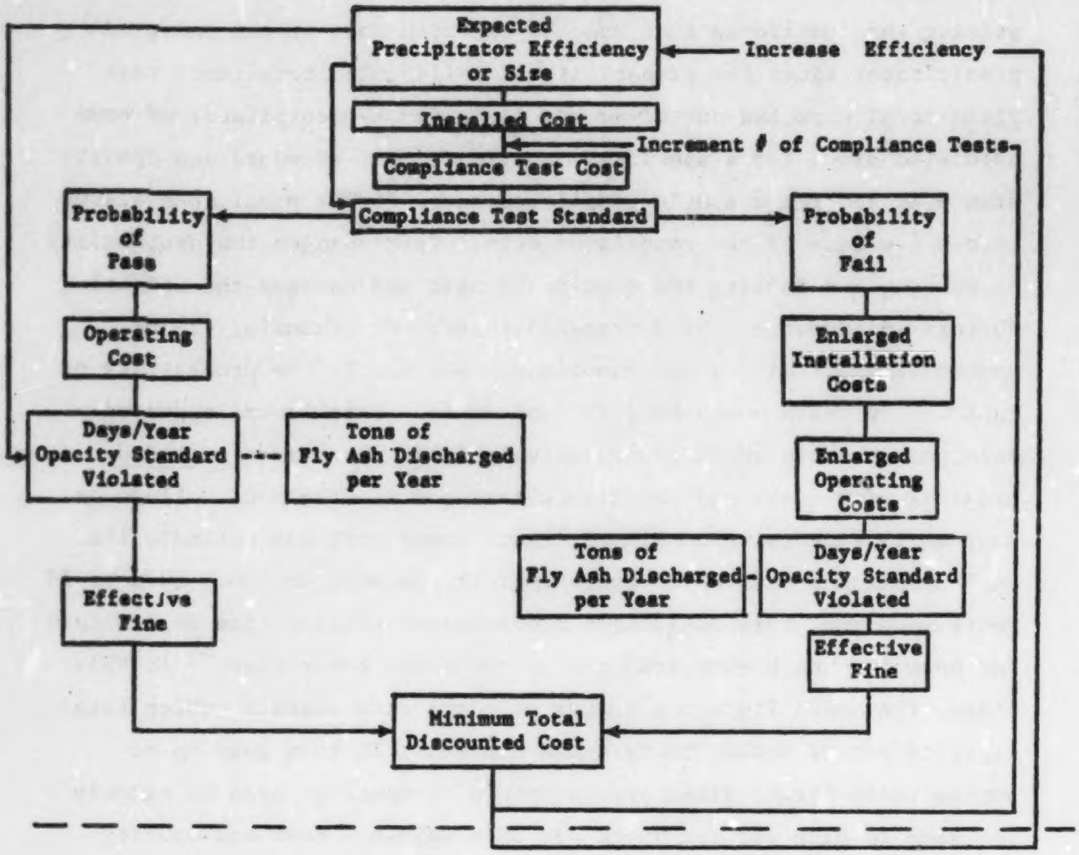
precipitator) has a lower "first day" collection efficiency (F1 versus I1) and consequently smaller dimensions and smaller installation cost since "first day" efficiency is a proxy for precipitator size. Hence, in comparison with a larger inflexilbe precipitator, a smaller sized flexible precipitator can produce the same average collection efficiency over an operating cycle. As we show later, at high collection efficiencies the cost savings from these smaller dimensions outweigh the extra flexible instrumentation costs making flexible precipitator technology the less costly of the two alternatives.

The Legal Enforcement Model. Figure 5 is a diagram of the model used to analyze implementation and enforcement scenarios S1, S2, S3, and S4 (the legal enforcement options). The model is basically a cost minimizing model. It considers a number of precipitators of different sizes and consequently different expected collection efficiencies. For each precipitator the model computes the probability of passing a start-up compliance test at some specified compliance test standard. (This is described in further detail at a later point.) It also computes the expected number of days per year when each precipitator would violate a specified opacity standard. Using these two pieces of information it then computes and sums costs in order to determine total expected costs.

The model begins by computing and summing precipitator installation costs and compliance test costs. Using the probability of passing the compliance test as a weighting factor it then adds in operating, maintenance and stack monitoring costs plus fines for violating the opacity standard, all of these costs, of course, having been computed for a precipitator of the originally specified size. A given precipitator, however, may fail the compliance test. If it fails the model assumes that the precipitator is enlarged to a size which has virtually no probability of failing a subsequent compliance test. In such cases, a power plant would then incur the installation and penalty costs[12] for an enlarged precipitator and its operating,

Figure 5

Simulation Model
Scenarios S1-S4*


Expected Precipitator Efficiency or Size
Increase Efficiency
Installed Cost
Increment # of Compliance Tests
Compliance Test Cost
Probability of Pass
Compliance Test Standard
Probability of Fail
Operating Cost
Enlarged Installation Costs
Days/Year Opacity Standard Violated
Tons of Fly Ash Discharged per Year
Enlarged Operating Costs
Tons of Fly Ash Discharged per Year
Days/Year Opacity Standard Violated
Effective Fine
Effective Fine
Minimum Total Discounted Cost

Total Discounted Cost = Installation Cost + Compliance Test Cost +
(Probability of Pass) x (Operating Cost + Effective Fine) +
(Probability of Fail) x (Enlarged Installation Cost +
Enlarged Operating Cost + Enlarged Effective Fine)

Effective Fine = { (Day/Year Opacity Std. Violated)x(Fine/Day)x(Prob. of Conv.), Scenarios S1 and S2
(Tons of Fly Ash Discharged)x(Tax/Ton), Scenarios S3 and S4

* Explicit equations and parameter values for this model are presented in an attached appendix.

maintenance and stack monitoring costs plus fines for violating a specified opacity standard during operation of the enlarged precipitator. The model sums these costs and uses the probability of failing the compliance test as a weighting factor. The sum of the expected cost for the original precipitator times the probability of passing the compliance test and the expected cost of the enlarged precipitator times the probability of failing the compliance test yield total expected out-of-pocket costs for a precipitator of some specified size, for a specified compliance test standard and opacity standard, and for a single compliance test.[13/] The model then allows successive runs of the compliance test. This changes the probability of passing and failing the compliance test and changes the weighting factors in computing total expected costs. For example, if the probability of fail in one compliance test is .7, the probability of fail in two tests would be $(.7)^2$ and so on. This lowers expected enlargement costs which are relatively large but raises *expected* original size costs and compliance test costs. The model allows as many as 15 successive compliance tests based upon the estimate that each compliance test takes approximately one week and that even if 15 tests were run, this would keep precipitator testing time well within the normal 6 month shakedown period for a new power plant. At this stage, the model finds the number of compliance tests at which total expected out-of-pocket costs are a minimum. It then goes on to successively larger sized precipitators, computing costs in exactly the same fashion for the given set of compliance test and opacity standards. It also holds constant throughout, the flue gas flow rate, the number of averaged stack samples taken during a compliance test and the expected fine for violating the opacity standard (see below). As a final step it finds the precipitator size or efficiency which minimizes total expected out-of-pocket costs to the firm for the given set of enforcement policy parameters. The set of exogenous enforcement policy parameters is then changed and the model rerun.

Each case simulated by the model actually entails 100 iterations.

Each cost computation in a particular run is based upon a Monte Carlo selection of cost factors from Beta distributions which are keyed to econometric and engineering estimates of the relevant cost factors. (See Dienemann (1966) and Watson (1973 and 1974).) The minimum total expected cost is the average of the minimums from the 100 iterations.[14] Each iteration, using a different randomly generated set of costing factors, selects the precipitator design which minimizes costs. This random selection process is reinitialized at the same starting value for each new set of enforcement policy parameters. This prevents firm behavior from being confounded in the simulation by differential stochastic variation of the costing parameters. The estimated minimum costs are also total discounted costs where the discounting reflects usage and electric utility costing conventions over a 30 year period, this being the normal lifetime of a new power plant and its precipitator.

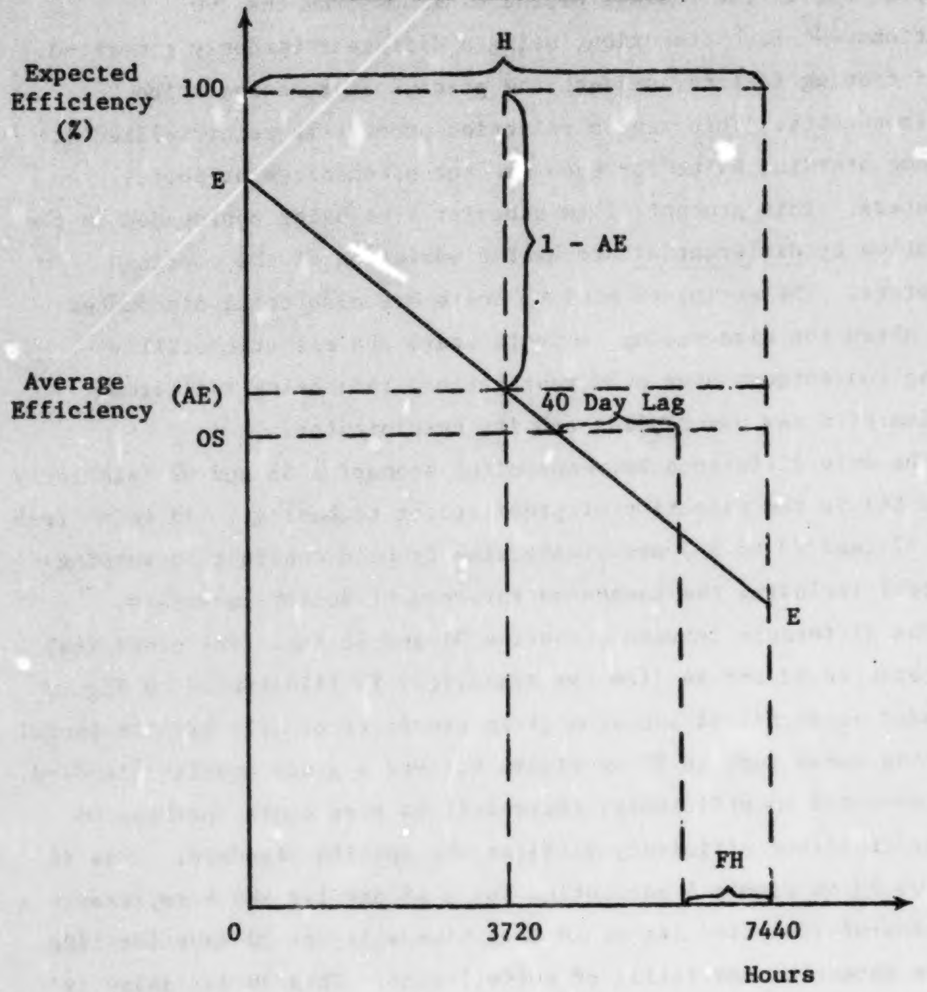
The only difference between policy scenarios S1 and S2 (similarly S3 and S4) is the selection of precipitator technology. In going from S1 to S2 (and S3 to S4) everything else is held constant in running the model including the exogenous enforcement policy paramters.

The difference between scenarios S1 and S2 (the fine scenarios) and scenarios S3 and S4 (the tax scenarios) is illustrated by Figure 6. Under scenarios S1 and S2 a given precipitator will have an annual operating curve such as EE in Figure 6. For a given opacity standard, OS, (converted to efficiency) there will be some hours (perhaps 0) when precipitator efficiency violates the opacity standard. This is shown by FH in Figure 6 accounting for a 40 day lag which represents a detection-of-violation lag of 10 days plus a lag of 30 days for time between detection and filing of a civil suit. This 30 day delay is used to insure that the violation is not just a chance occurrence and to provide the time necessary to prepare the control agency's case. Effective fine is computed as FH/24 times fine per day times probability of conviction.

Under the tax scenarios, S3 and S4, a tax is paid on every ton of

Figure 6

Fines and Emission Taxes



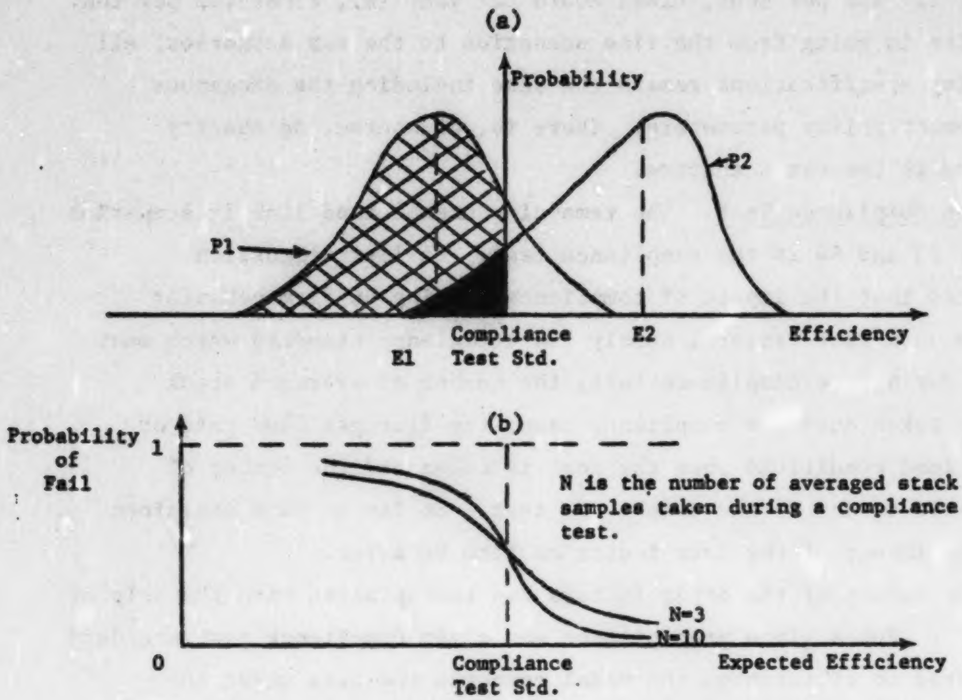
emitted fly ash. In terms of Figure 6, annual total emission tax would be 1-AE times engineering factors which convert efficiency to tons of fly ash per hour, times hours per year (H), times tax per ton. Otherwise in going from the fine scenarios to the tax scenarios, all parameter specifications remain the same including the exogenous enforcement policy parameters. There is, of course, no opacity standard in the tax scenarios.

The Compliance Test. The remaining unexplained link in scenarios S1, S2, S3 and S4 is the compliance test. Earlier discussion indicated that the impact of compliance testing on firm behavior depends upon four factors, namely the efficiency standard which must be met during the compliance test, the number of averaged stack samples taken during a compliance test, the flue gas flow rate or boiler load conditions when the test is taken and the number of successive reruns of the compliance test. So far we have explained only the impact of the last factor on firm behavior.

The impact of the other factors can be explained with the help of Figure 7. For a given precipitator and given compliance test standard (converted to efficiency) the model computes the area under the probability density function of efficiencies which is below the given compliance test standard (see Watson (1973)). This area is the probability of fail, and one minus this area is the probability of pass. These factors then become the weights which pre-multiply original-size costs and enlarged costs in the simulation model. An example is shown in Figure 7a. P1 is the probability density function for precipitator one; P2 is the probability density function for precipitator two. E1 and E2 are their respective expected first day efficiencies. Precipitator two which is larger than precipitator one (and which consequently has a higher expected first day efficiency) has a smaller probability (shaded area) of failing the given compliance test than does precipitator one (the cross hatched area). Tightening the compliance test standard would increase the probability of fail for both precipitators one and two. This would provide larger

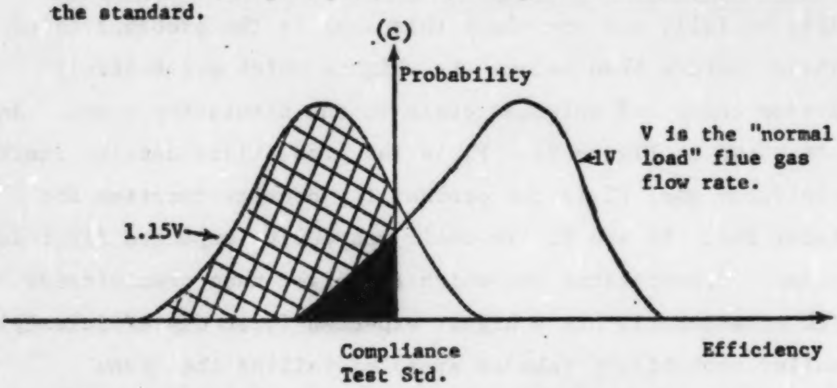
Figure 7

Compliance Test Tradeoffs



N is the number of averaged stack samples taken during a compliance test.

As N increases, probability of fail decreases for precipitators with expected efficiencies above the compliance test standard and increases for precipitators with expected efficiencies below the standard.



V is the "normal load" flue gas flow rate.

As the flue gas flow rate increases, probability of fail increases for a precipitator of fixed size.

weighting factors for the relatively large enlargement costs and would tend, consequently, to induce firms to select more efficient and more costly precipitators. Thus, other things constant, cost-minimizing firms would favor lax compliance test standards.

These probabilities and their associated density functions are actually computed for a varying number of averaged compliance test stack samples. Recall that federally promulgated regulations require that the average of at least three separate stack samples must provide a reading which satisfies the compliance test standard before a power plant is allowed to begin full time operation. The model simulates this by repeated sampling from the appropriate density functions, averaging of the sample efficiencies, and computation of pass and fail probabilities. In effect, it generates a series of power functions like those shown in Figure 7b.[15/] As the number of averaged stack samples is increased, cost minimizing power plants will tend to pick more efficient precipitators. This occurs because higher numbers of stack samples provide probabilities of pass and fail (cost weighting factors in the model) which favor more efficient precipitators. For example, as the number of stack samples taken during a compliance test increases, probability of fail decreases for precipitators with expected efficiencies above the compliance test standard and increases for precipitators with expected efficiencies below the standard. Precipitators with expected efficiencies below the standard rather than above would have relatively higher weighting factors for the relatively large enlargement costs. This would tend to induce firms to pick larger and hence more efficient precipitators.

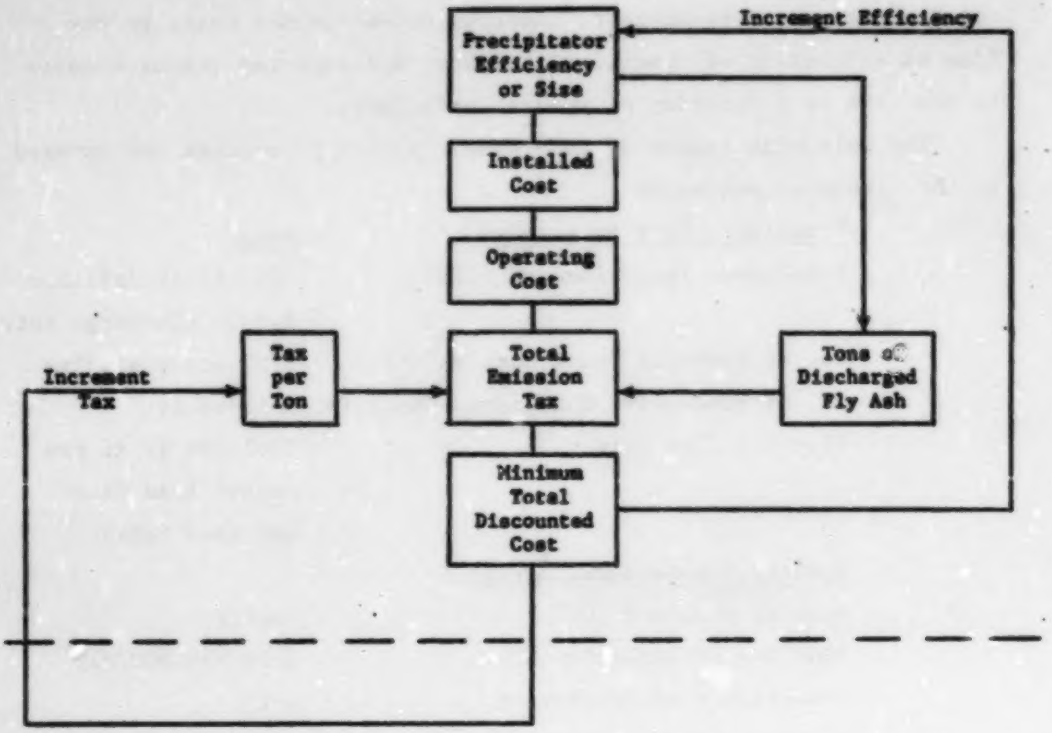
The probability density functions associated with the compliance tests are also affected by boiler load conditions during compliance tests. When boilers are loaded at peaking levels, the flue gas flow rate through a precipitator can be about 15% above the normal level. Figure 7c shows a representative probability of fail (cross hatched area) for peak load conditions and probability of fail (shaded area) for normal load conditions. Clearly probability of fail is less under normal load conditions. A cost minimizing firm would favor low load conditions during the compliance test since this provides smaller weighting factors for the relatively large enlargement costs and consequently lower total expected costs. On the other hand, compliance tests under high load conditions make the compliance test more effective in enforcing a given fly ash emission standard. The model allows for flue gas flow rate variations in simulating compliance tests and hence in computing probabilities of pass and fail.

The Emission Tax Model. Figure 8 shows the cost model used to simulate the emission-tax-only scenarios, S5 and S6. For a precipitator of given size and for a given emission tax per ton of fly ash discharged, the model computes total emission taxes. To these it adds installation costs, operating, maintenance and stack monitoring costs to obtain total expected out-of-pocket costs. Precipitator size is then incremented and total costs recomputed. Computation is truncated when the model finds the precipitator size or efficiency which minimizes the sum of precipitator costs and total taxes for the given emission tax. The emission tax, which is a constant value per ton, is then incremented and the model rerun. Unit emission taxes which vary over time with meteorological conditions for example, and unit taxes which increase as total emissions increase, are not specifically considered. However, such emission taxes would not change our basic results.

As before selection of cost minimizing expected precipitator efficiency (in this case for a given emission tax) is based upon the average of 100 iterations of the model. Each iteration, using a randomly generated set of costing factors selects the precipitator design which minimizes costs. The random selection process is reinitialized at the same starting value for each new emission tax so that firm behavior as a function of emission tax is not muddied in the simulation by differential stochastic variation of the costing parameters. Policy scenario 5 assumes inflexible technology, scenario 6 assumes flexible technology; everything else is kept constant

Figure 6

Simulation Model
Scenarios S5 and S6*


Increment Efficiency
Precipitator Efficiency or Size
Installed Cost
Operating Cost
Increment Tax
Tax per Ton
Total Emission Tax
Tons of Discharged Fly Ash
Minimum Total Discounted Cost

Total Discounted Cost = Installation Cost + Operating Cost + Total Emission Tax

***Explicit equations and parameter values for this model are presented in an attached appendix.**

between the two scenarios.

Simulation Results. The objective of the simulation model is to provide cost and performance functions for each of the policy scenarios. The following functions are of interest: expected out-of-pocket costs to the firm as a function of enforcement policy parameters, expected precipitator efficiency as a function of enforcement policy parameters, expected out-of-pocket costs to the firm as a function of removal efficiency, and expected resource costs to the firm as a function of removal efficiency.

The following ranges of enforcement policy parameters are covered in the simulated scenarios:

Compliance Test Parameters	Range
Compliance Test Standard (CTS)	.04-.14 lb./million B.t.u. discharge rate
No. of Averaged Stack Samples (N)	3-50 stack samples
No. of Successive Compliance Tests (M)	3-15 tests
Flue Gas Flow Rate (R)	1V-1.15V (V is the normal load flue gas flow rate)
Opacity Standard Parameters	
Opacity Standard (OS)	5%-40%
Fine/Day of Violation (F)	$500-$50,000/day
Probability of Conviction	0-1
Emission Tax Parameter	
Tax/Ton of Fly Ash (T)	$5-$180/ton

Scenarios S1 through S4 use a combination of structured and randomly chosen enforcement policy parameters. Our objective was to uniformly cover a relatively wide range of enforcement policy combinations. In all, 50 different policy combinations were selected for these simulations. In the case of the emission-tax-only scenarios, the model was run for only a maximum of 10 different tax rates since each emission tax produces a unique least-cost response. For each set of enforcement policy parameters the model computes expected precipitator efficiency, expected least-costs of fly ash control and expected fines or emission taxes paid. Furthermore, in order to provide for differential response due mainly to economies of scale, the model considers four different plant sizes, 1300 megawatts, 800 megawatts, 200 megawatts, and 25 megawatts. That is, for each power plant size per scenario, the simulation experiments provide 50 observations (scenarios S1 through S4) or a maximum of 10 observations (scenarios S5 and S6) on firm least-cost behavior as a function of enforcement policy parameters.

Since the model is too complex to solve analytically regression analysis has been used to summarize these "experimental" data. In effect, this "solves" the model. The following functions have been fitted:

Scenarios S1 through S4

$$(9)\quad C=A(CTS)^{a_1}(N)^{a_2}e^{MD\cdot a_3}(R)^{a_4}(OS)^{a_5}(F \text{ or } T)^{a_6}$$

$$(10)\quad E=100-100\cdot EXP[-B(CTS)^{b_1}(N)^{b_2}e^{MD\cdot b_3}(R)^{b_4}(OS)^{b_5}(F \text{ or } T)^{b_6}]$$

Scenarios S5 and S6

$$(11)\quad C=A(T)^{a_6}$$

$$(12)\quad E=100-100\cdot EXP[-B(T)^{b_6}]$$

All Scenarios[16]

$$(13)\quad C=D(\ln(100/(100-E)))^{d_1}(N)^{d_2}$$

$$(14)\quad C-FT=G(\ln(100/(100-E)))^{g_1}(N)^{g_2}$$

C is total expected discounted cost. It includes out-of-pocket firm pollution control costs, associated firm management costs, and total fines or emission taxes. E is average expected precipitator collection efficiency (%) during base-load years. FT is total expected discounted fine or emission tax. MD is a dummy variable which is one when the maximum number of allowable successive compliance tests is 3 and zero when greater than 3.

Assuming appropriate signs for coefficients, equations (10) and (12) indicate that collection efficiency approaches 100% as enforcement is made extremely stringent. This is consistent with the known operating characteristics of electrostatic precipitators (White (1963)). Cost equations (13) and (14) are consistent with optimizing behavior whereby accounting costs for pollution control are minimized subject to an efficiency function (Watson (1970)). Equations (9) and (11) are reduced form cost minimizing equations derived by substituting equations (10) and (12) into a form-(13) cost equation. These six equations provide a consistent set of equations for determining the functions which are of interest. Equations (9) and (11) are used to derive out-of-pocket pollution control and management costs for the firm as a function of enforcement policy. Equations (10) and (12) are used to derive precipitator efficiency as a function of enforcement policy. Equation (13) is used to derive the firm's out-of-pocket control and management cost including fines or emission taxes as a function of precipitator efficiency and equation (14) is used to derive resource costs--pollution control and mangement cost excluding fines or emission taxes--as a function of precipitator efficiency.

Since the basic simulation model contains functional forms which are similar to equations (9) through (14) (see appendix), high multiple correlations from the regression analyses should not be surprising. Thus the regressions cannot be regarded as a test of the goodness of fit of equations (9) through (14). On the other hand, individual enforcement policy coefficients within the indicated functional forms are not constrained in the simulation model. They may or may not be significant depending upon least cost tradeoffs. Therefore in "solving" the model the regressions can help to determine which enforcement policy coefficients are significant and therefore which exert an influence on the firm's control efforts.

Estimates of the regression coefficients are listed in Tables 1 through 5. Prior expectation is that the regression coefficients for the compliance test standard and the opacity standard will be negative and that all the other regression coefficients will be positive. Lower numbers for the compliance test and opacity standards represent

Table 1

Regression Coefficients from Simulation Analyses*
S1: Compliance Test with Fine for Violating an Opacity Standard
(Inflexible Technology)

Dependent Variable**	Constant	$\ln \frac{100}{100-E}$	Compliance Test Standard	No. of Test Samples	No. of Compliance Tests	Flue Gas Rate	Opacity Standard	Fine	R^2
			1300MW						
Cost(9)	Exp (8.86)		-.073	.012	.01***	.495	-.04	NS	.91
Efficiency(10)	Exp (1.24)		-.168	.032	.05	1.26	-.134	NS	.88
Cost(13)	Exp (8.46)	.368							.97
Cost-Fine(14)	Exp (8.46)	.368							.97
			800MW						
Cost(9)	Exp (8.45)		-.075	.012	.01****	.505	-.037	NS	.92
Efficiency(10)	Exp (1.22)		-.17	.032	.05	1.26	-.128	NS	.89
Cost(13)	Exp (8.06)	.371							.97
Cost-Fine(14)	Exp (8.06)	.371							.97
			200MW						
Cost(9)	Exp (7.42)		-.072	.011	NS	.459	-.024	NS	.94
Efficiency(10)	Exp (1.12)		-.185	.034	NS	1.21	-.097	NS	.92
Cost(13)	Exp (7.07)	.349							.96
Cost-Fine(14)	Exp (7.07)	.349							.96
			25MW						
Cost(9)	Exp (6.46)		-.043	.013	NS	.275	-.008*****	NS	.88
Efficiency(10)	Exp (1.19)		-.194	NS	NS	1.18	-.06	NS	.87
Cost(13)	Exp (6.25)	.198		.015					.84
Cost-Fine(14)	Exp (6.25)	.198		.015					.84

*Significant at the .01 level or smaller unless otherwise indicated

NS Non-significant

**Dollar amounts are in thousands of 1967 dollars. The numbers in parentheses indicate the functional forms fitted.

***Significant at the .05 level

****Significant at the .10 level

*****Significant at the .02 level

Table 2

Regression Coefficients from Simulation Analyses*
S2: Compliance Test with Fine for Violating an Opacity Standard
(Flexible Technology)

Dependent Variable**	Constant	$\ln \frac{100}{100-E}$	Compliance Test Standard	No. of Test Samples	No. of Compliance Tests	Flue Gas Rate	Opacity Standard	Fine	R^2
			1300MW						
Cost(9)	Exp (8.79)		-.082	.011	.02	.53	-.013	NS	.93
Efficiency(10)	Exp (.917)		-.223	.042	.07	1.34	-.049	NS	.88
Cost(13)	Exp (8.49)	.346							.97
Cost-Fine(14)	Exp (8.49)	.346							.97
			800MW						
Cost(9)	Exp (8.38)		-.083	.011	.01	.549	-.012	NS	.94
Efficiency(10)	Exp (.97)		-.21	.041	.06	1.31	-.049	NS	.86
Cost(13)	Exp (8.07)	.357							.95
Cost-Fine(14)	Exp (8.07)	.357							.95
			200MW						
Cost(9)	Exp (7.39)		-.074	.01	NS	.515	-.008***	NS	.94
Efficiency(10)	Exp (.917)		-.226	.042	.03****	1.43	-.033	NS	.92
Cost(13)	Exp (7.1)	.317							.95
Cost-Fine(14)	Exp (7.1)	.317							.95
			25MW						
Cost(9)	Exp (6.46)		-.043	.011	NS	.322	NS	NS	.81
Efficiency(10)	Exp (1.24)		-.187	NS	NS	1.47	-.029	NS	.86
Cost(13)	Exp (6.23)	.202		.012					.76
Cost-Fine(14)	Exp (6.23)	.202		.012					.76

*Significant at the .01 level or smaller unless otherwise indicated
NS Non-significant
**Dollar amounts are in thousands of 1967 dollars. The numbers in parentheses indicate the functional forms fitted.
***Significant at the .02 level
****Significant at the .03 level

Table 3

Regression Coefficients from Simulation Analyses*
S3: Compliance Test with Tax on Emitted Fly Ash
(Inflexible Technology)

Dependent Variable**	Constant	$\ln \frac{100}{100-E}$	Compliance Test Standard	No. of Test Samples	No. of Compliance Tests	Flue Gas Rate	Tax	R^2
			1300MW					
Cost(9)	Exp (8.82)		-.017	NS	NS	.058***	.064	.97
Efficiency(10)	Exp (.88)		-.077	NS	NS	.378	.132	.89
Cost(13)	Exp (8.43)	.427						.93
Cost-Tax(14)	Exp (8.46)	.367						.99
			800MW					
Cost(9)	Exp (8.41)		-.02	NS	NS	.074****	.062	.96
Efficiency(10)	Exp (.89)		-.081	NS	NS	.425	.124	.87
Cost(13)	Exp (8.02)	.431						.92
Cost-Tax(14)	Exp (8.05)	.370						.98
			200MW					
Cost(9)	Exp (7.39)		-.027	.006	NS	.118	.047	.92
Efficiency(10)	Exp (.89)		-.108	NS	NS	.573	.1	.83
Cost(13)	Exp (7.05)	.376		.005***				.89
Cost-Tax(14)	Exp (7.08)	.329		.005				.93
			25MW					
Cost(9)	Exp (6.43)		-.031	.014	NS	.131	.019	.77
Efficiency	Exp (1.07)		-.14	NS	NS	.79	.045	.71
Cost(13)	Exp (6.23)	.212		.017				.71
Cost-Tax(14)	Exp (6.20)	.224		.017				.79

*Significant at the .01 level or smaller unless otherwise indicated
NS Non-significant
**Dollar amounts are in thousands of 1967 dollars. The numbers in parentheses indicate the functional forms fitted.
*****Significant at the .08 level**
******Significant at the .04 level**

Table 4

Regression Coefficients from Simulation Analyses*
S4: Compliance Test with Tax on Emitted Fly Ash
(Flexible Technology)

Dependent Variable**	Constant	$\ln \frac{100}{100-E}$	Compliance Test Standard	No. of Test Samples	No. of Compliance Tests	Flue Gas Rate	Tax	R^2
			1300MW					
Cost(9)	Exp (8.85)		-.028	NS	NS	.132	.045	.92
Efficiency(10)	Exp (.96)		-.12	NS	.04***	.617	.096	.83
Cost(13)	Exp (8.51)	.353						.88
Cost-Tax(14)	Exp (8.47)	.349						.97
			800MW					
Cost(9)	Exp (8.84)		-.032	NS	NS	.155	.043	.91
Efficiency(10)	Exp (.95)		-.123	NS	.04***	.66	.093	.82
Cost(13)	Exp (8.11)	.35						.90
Cost-Tax(14)	Exp (8.08)	.34						.95
			200MW					
Cost(9)	Exp (7.42)		-.04	.006	NS	.211	.031	.87
Efficiency(10)	Exp (.96)		-.15	.014****	NS	.85	.069	.84
Cost(13)	Exp (7.13)	.315						.88
Cost-Tax(14)	Exp (7.08)	.323						.90
			25MW					
Cost(9)	Exp (6.45)		-.034	.013	NS	.208	.01	.78
Efficiency(10)	Exp (1.24)		-.16	NS	NS	1.12	.02*****	.77
Cost(13)	Exp (6.24)	.189		.017				.75
Cost-Tax(14)	Exp (6.16)	.23		.016				.79

*Significant at the .01 level or smaller unless otherwise indicated
NS Non-significant
**Dollar amounts are in thousands of 1967 dollars. The numbers in parentheses indicate the functional forms fitted.
***Significant at the .02 level
****Significant at the .05 level
*****Significant at the .03 level

Table 5

Regression Coefficients from Simulation Analyses*
S5 and S6: Emission Tax Only

	S5: Inflexible Technology				S6: Flexible Technology			
Dependent Variable**	Constant	$\ln \frac{100}{100-E}$	Tax	R^2	Constant	$\ln \frac{100}{100-E}$	Tax	R^2
		1300MW				1300MW		
Cost(11)	Exp (8.8)		.081	.99	Exp (8.8)		.072	.99
Efficiency(12)	Exp (.466)		.298	.98	Exp (.52)		.289	.95
Cost(13)	Exp (8.7)	.27		.99	Exp (8.7)	.244		.99
Cost-Tax(14)	Exp (8.5)	.355		.99	Exp (8.5)	.33		.99
		800MW				800MW		
Cost(11)	Exp (8.4)		.081	.99	Exp (8.4)		.072	.99
Efficiency(12)	Exp (.45)		.296	.98	Exp (.31)		.287	.95
Cost(13)	Exp (8.3)	.271		.99	Exp (8.3)	.246		.99
Cost-Tax(14)	Exp (8.1)	.354		.99	Exp (8.1)	.331		.99
		200MW				200MW		
Cost(11)	Exp (7.4)		.075	.99	Exp (7.4)		.067	.99
Efficiency(12)	Exp (.40)		.291	.98	Exp (.45)		.282	.96
Cost(13)	Exp (7.3)	.254		.99	Exp (7.3)	.232		.99
Cost-Tax(14)	Exp (7.1)	.325		.99	Exp (7.1)	.305		.99
		25MW				25MW		
Cost(11)	Exp (6.4)		.04	.99	Exp (6.4)		.0365	.99
Efficiency(12)	Exp (.28)		.296	.98	Exp (.31)		.299	.96
Cost(13)	Exp (6.4)	.135		.99	Exp (6.4)	.12		.99
Cost-Tax(14)	Exp (6.3)	.164		.99	Exp (6.3)	.151		.99

*Significant at the .001 level or smaller

**Dollar amounts are in thousands of 1967 dollars. The numbers in parentheses indicate the functional forms fitted.

tighter standards. With tight standards, firms will tend to pick relatively large precipitators in order to avoid enlargement costs and fines. Hence the compliance test and opacity standard will be negatively related to precipitator efficiency and cost. Previously it was shown that the probability of failing the compliance test increases (1) as the number of averaged compliance test samples increases (given a "shoddy" device), (2) as the allowed number of successive compliance tests declines, and (3) as the flue gas flow rate during the compliance test increases. Accordingly, increases in these enforcement parameters will provide relatively large weighting factors for large enlargement costs. To avoid this, firms will tend to pick more efficient and higher cost precipitators, producing a positive relationship between these enforcement parameters and precipitator efficiency and cost. A positive relationship between emission tax and precipitator cost and efficiency, and between cost and logarithmic transformation of efficiency is also expected. The signs of the estimated regression coefficients (see Tables 1 through 5) are consistent with these prior expectations and the fits are very good.

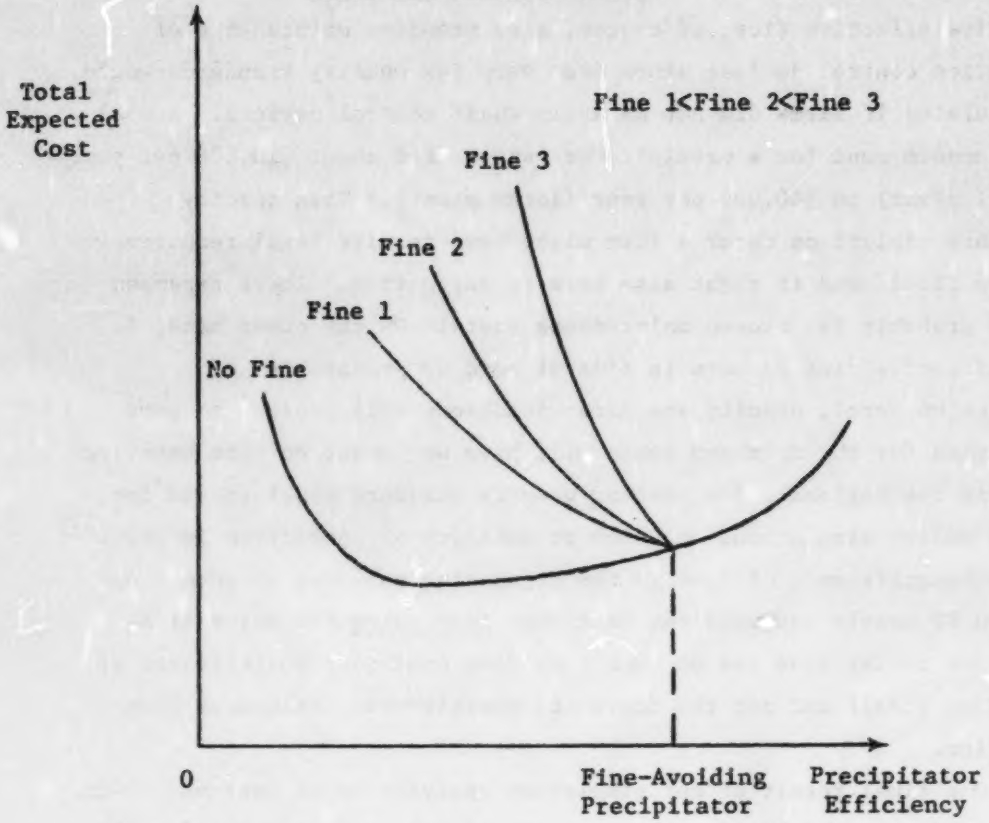
The role of effective fine (days x fine/day x probability of conviction) in scenarios S1 and S2 needs further elaboration. Note that fine appears to be an insignificant determinant of behavior in scenarios S1 and S2. This is misleading. The probability of conviction has been subsumed into the opacity standard. Whenever probability of conviction is zero, opacity standard was set equal to 40% in the regression analyses, in effect making the opacity standard non-operative since 40% is a large value or a relatively lax opacity standard. Obversely the role of a positive effective fine is to help make the opacity standard operative. In the model itself, costs (excluding effective fines) are nearly constant over a wide range of precipitator sizes. Consequently, the impact of any positive effective fine is to usually induce a cost minimizing firm to pick a fine-avoiding precipitator. Furthermore, increasing the dollar fine per conviction usually makes the cost curve more steep around the least cost precipitator size, but does not shift the least cost point (see Figure 9). Hence, the impact of effective fine on firm behavior is a "zero-one" effect. If the effective fine is any positive value (fine positive, probability of conviction positive) then the promulgated opacity standard is operative (i.e., the opacity standard impacts firm behavior in relationship to its specified value). A positive effective fine, of course, also promotes maintenance of pollution control devices since even very lax opacity standards would be violated if firms did not maintain their control devices. Annual maintenance cost for a precipitator ranges from about $10,000 per year (small plant) to $40,000 per year (large plant). When opacity standard violations occur a firm might have to hire legal resources to defend itself and it might also have to pay a fine. These expenses would probably far exceed maintenance costs. On the other hand, if the effective fine is zero (a fine of zero or probability of conviction zero), opacity standard violations will produce no cost penalties for the firm and hence will have no impact on firm behavior. This is the rationale for setting opacity standard equal to 40% for those policy simulations in which probability of conviction is zero.[17] The nonsignificance of fine in the regression analyses of scenarios S1 and S2 merely reflects the fact that increasing the value of a positive dollar fine has no impact on firm behavior; positiveness of the fine itself and not the degree of positiveness influences firm behavior.

One final result of our simulation analysis is of interest. Our best assessment of EPA's current choice of policy parameters for the enforcement of the new source performance standards for coal-fired power plants is:

Compliance Test Standard = 0.1 lb./million B.t.u.
No. of Successive Compliance Tests = 15 or less
No. of Averaged Stack Samples = 3
Flue Gas Flow Rate = 1.1V

Figure 9

Fines and Control Effort



Opacity Standard = 30%
Fine/Day of Violation = \$500-\$50,000/day

Using these values in the model, we find that most plants will control to less than the standard and almost never be cited for a violation. In fact, plants larger than 100 megawatts will be in violation from 50 to 70 percent of the time depending upon plant size (see Table 6). The reason why plants are not cited for a violation is that the enforced opacity standard allows about three times the emissions of the compliance test standard. We also find that small plants control to a higher level than large plants even though it is relatively more expensive for them to do so. This is because large plants enjoy economies of scale which allow them (relative to small plants) to make more favorable cost-reducing tradeoffs against enforcement policy parameters. Furthermore, all firms choose inflexible technology since its out-of-pocket cost to the firm is less than flexible technology. This is an inefficient choice for society, however, since the real resource cost of the same level of average control using flexible technology is less. In fact, savings in the resource costs of control are probably an underestimate of the societal savings since flexible technology has a higher last day efficiency than inflexible technology. Thus, if marginal damages decline with control as is usually the case, then the increased damages due to a lower first day efficiency for the flexible device are more than offset by the higher damage savings due to its greater last day efficiency. Furthermore, damages are likely to be suboptimally high because the current combination of policy parameters yields a level of control below the fly ash standard and there are some indications that the standard is approximately correct in terms of benefits and costs (Watson (1974)).

Table 6

Current Enforcement Practice

Plant Size (Megawatts)	Expected Average Efficiency* (%, Inflexible Technology)	Expected Cost (1000's of 1967 Dollars, Discounted)	Expected Time in Violation* (%)
25	99.1%	$ 720	0%
200	98.0	1,900	61
800	97.7	5,200	70
1300	97.7	7,800	70

*During base load year at normal flue gas flow rates. Time in violation would be higher and average efficiency lower to the extent that plants are operated above normal loads, for example, under peak load demand conditions.

SECTION V

POLICY ANALYSIS

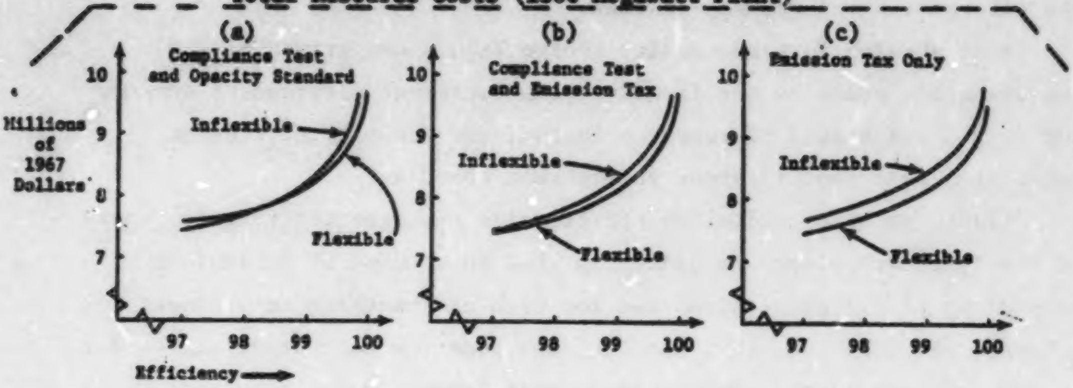
Cost Comparisons. We can now use our simulation results, summarized by our regression equations, to investigate tradeoffs among the alternative enforcement schemes.

Four straightforward results evolve from a comparison of out-of-pocket costs to the firm over the different enforcement schemes and from a comparison of resource costs (cost minus total fine or total tax) over the different enforcement schemes.

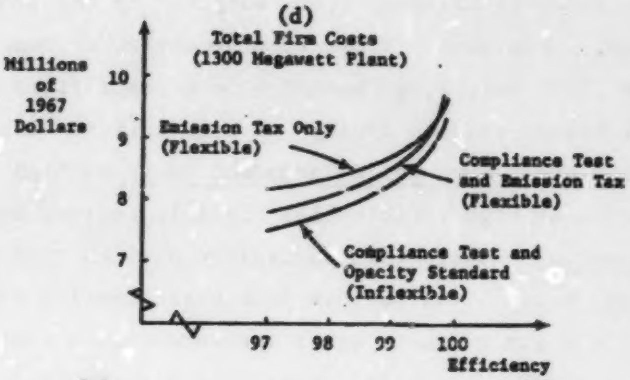
First, at high collection efficiencies the expected resource costs of flexible technology are generally less than those of inflexible technology at all plant sizes and for each of the three enforcement schemes. Figures 10a, 10b, and 10c show some representative curves for a 1300 megawatt plant. Under enforcement schemes using compliance tests, firms will incur enlargement costs weighted by the probability of failing the compliance test. These enlargement costs tend to be quite large while their weighting factors--the probabilities of compliance test failure--tend to decline at high efficiencies. This produces relatively small expected enlargement costs at high collection efficiencies. Hence at high efficiencies flexible devices have smaller expected resource costs than inflexible devices (for the same average efficiency) because the savings from their smaller original-size costs exceed the sum of their extra instrumentation costs, their higher power input costs, and their larger (but relatively small) enlargement costs. This is demonstrated by Figures 10a and 10b: flexible costs are less than inflexible when collection efficiency is approximately 97% or greater. Under emission-tax-only enforcement and at high collection efficiencies a flexible precipitator also has smaller expected resource costs than an inflexible precipitator (see Figure 10c). The reason is that the smaller original-size costs for flexible precipitators provide savings which exceed their extra instrumentation and power costs. In this case there is no question of a plant failing a compliance test and incurring enlargement costs.

Figure 10
Cost Comparisons

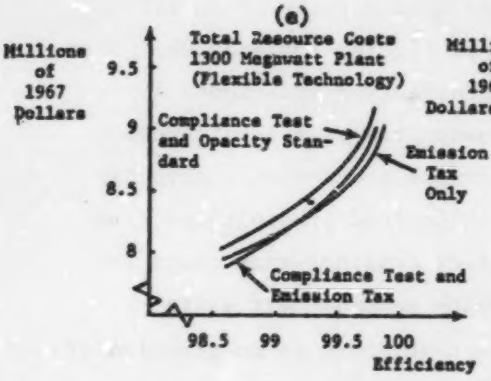
Total Resource Costs (1300 Megawatt Plant)



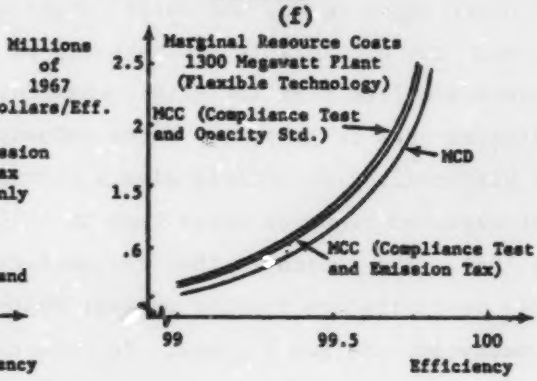
(d)
Total Firm Costs
(1300 Megawatt Plant)



(e)
Total Resource Costs
1300 Megawatt Plant
(Flexible Technology)



(f)
Marginal Resource Costs
1300 Megawatt Plant
(Flexible Technology)



Therefore since enlargement costs need not be overcome by flexible cost savings, flexible precipitators enjoy an even greater cost advantage over inflexible under emission-tax-only enforcement than they do under compliance test (with an opacity standard or emission tax) enforcement. This is demonstrated by the relatively larger cost advantage for flexible technology in Figure 10c; in Figures 10a and 10b flexible technology enjoys a relatively smaller cost advantage.

Second, the lowest out-of-pocket cost to the firm occurs with enforcement via a compliance test and opacity standard (with inflexible technology), the next from the lowest is a compliance test with emission tax (with flexible technology), and the third from the lowest is the emission tax only (with flexible technology). Out-of-pocket costs, of course, include fines and emission taxes paid under each of the enforcement schemes. Figure 10d presents each of these costs for a 1300 megawatt plant. On the other hand, a comparison of resource costs (all for flexible technology since we have just seen above that flexible is cheaper) gives the exact opposite ordering (see Figure 10e). Hence the enforcement schemes which use emission taxes and resource-saving flexible technology and which consequently are attractive to a cost-minimizing resource manager are unattractive to the firms being regulated and vice versa.[18/] An implication is that there will be some resistance by firms to a shift toward enforcement schemes which use emission taxes even though this is desirable from the viewpoint of resource cost minimization. We will have more to say about these matters at a later point.

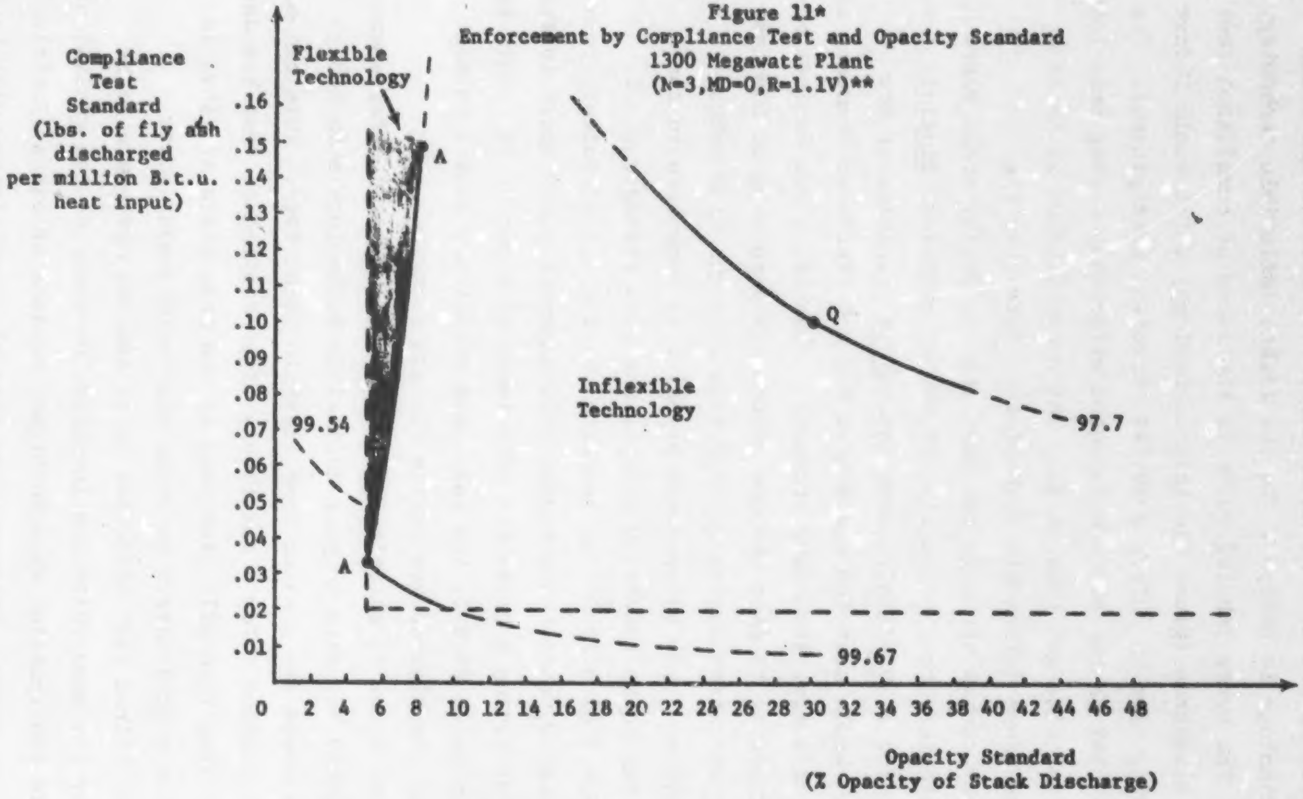
In our earlier discussion of efficient enforcement (p. 11) a distinction was made between resource costs of control only (MCD) and marginal resource costs of control including marginal firm management costs (MCC). We now have quantitative measures of these costs. Using our simulation regressions we have plotted marginal resource costs for a 1300 megawatt plant for each of our three alternative enforcement schemes (see Figure 10f). The emission-tax-only curve is the marginal resource cost of control only curve since under this enforcement scheme there are no differential management costs such as those associated with compliance testing. The other two curves are the marginal resource costs of control including firm management costs for the indicated enforcement schemes. On the average (at high efficiency levels) there is about a 6% difference between MCC and MCD under compliance-test-with-emission-tax enforcement and about a 6.6% difference under compliance-test-with-opacity-standard enforcement.[19/] It would appear that if a marginal benefit curve crosses these cost curves at high efficiency levels, using one or the other to determine "efficient" control levels results in approximately the same control level. It is well to recall however, (see p. 13) that the proper inclusion of marginal enforcement agency costs could significantly impact determination of efficient control levels.

Policy Frontiers. Particular technologies were deliberately specified in the above ordering of preferred costs by the firm. This is necessary because the firm in reacting to enforcement policy parameters chooses the precipitator size and technology which minimizes its costs. Indeed, different mixes of enforcement policy parameters will induce it to pick flexible technology in some cases and inflexible technology in others. We proceed now to investigate the conditions governing technology selection.

The curve labeled AA in Figure 11 is the locus of compliance test standards and opacity standards for which flexible technology control out-of-pocket costs (for a 1300 megawatt plant) equal inflexible technology control out-of-pocket costs. This locus is determined by setting costs as a function of enforcement policy parameters from scenarios S1 and S2, equal to each other. The dashed perpendiculars and the area to the northeast of these perpendiculars indicate approximate feasible choices for the compliance test and opacity standards. A compliance test standard of .2 and an opacity standard of 5 are factor increases of 5 and 4 respectively in current standards. It is doubtful that stricter nominal standards could be promulgated without serious legal challenges by affected industries.

Figure 11*

Enforcement by Compliance Test and Opacity Standard
1300 Megawatt Plant
(N=3,MD=0,R=1.1V)**



*Similar tradeoffs occur at other plant sizes.

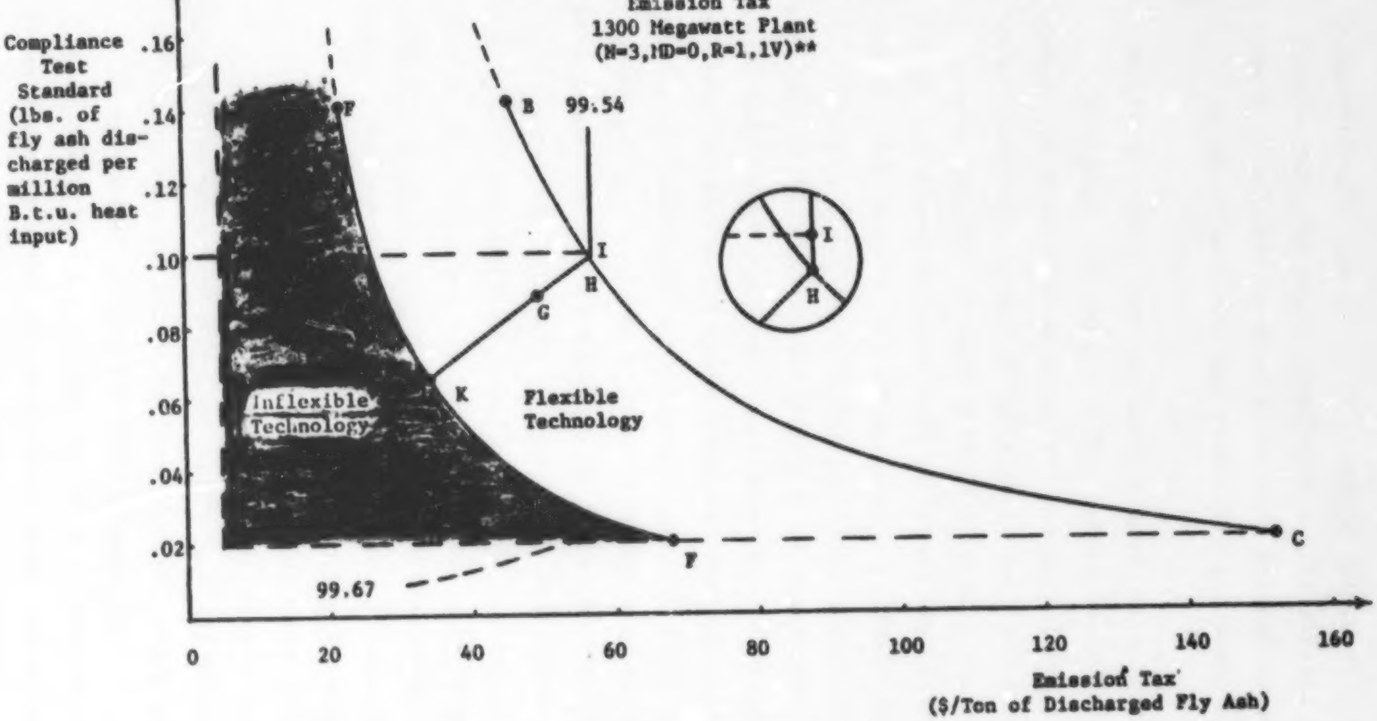
**An average of three stack samples (N=3), no limits on the number of successive compliance tests (MD=0), and an intermediate level for the flue gas flow rate (1.1V) are representative of current enforcement practice.

The shaded area to the left of AA is the policy area within which flexible technology is cheaper. To the right, inflexible technology is cheaper. The curve labeled 99.54 is the locus of compliance test and opacity standards (given flexible technology) which would induce a cost minimizing firm to select a 99.54% efficient precipitator. The efficiency 99.54% is the average expected efficiency during base-load years at normal flue gas flow rates. The curve labeled 99.67 is a similar locus given inflexible technology. Note that the iso-efficiency curves are only relevant for the policy areas where their technologies are less costly. A 99.54% efficient flexible precipitator and a 99.67% efficient inflexible precipitator are devices which would meet the new source fly ash discharge standard of .1 lb./million B.t.u. (two-hour average). That is, these devices have sufficient capacity to meet the new source standard even on the last day of their operating cycles at peak load flue gas flow rates (1.15V). Current legal enforcement practice is somewhere in the vicinity of the point labeled Q (compliance test standard of .1, opacity standard of 30%).[20/] As indicated by the iso-efficiency curve passing through Q, a cost minimizing 1300 megawatt plant would install a precipitator having a base-load efficiency of about 97.7%. This is substantially below 99.67%, the base-load efficiency needed to meet the federally promulgated new source fly ash standard.

Furthermore, as is clearly indicated, current legal enforcement practice induces the firm to pick inflexible technology even though its resource costs are greater than flexible technology. This can be explained as follows. For a relatively tight compliance test standard a cost minimizing firm will pick roughly the same sizes of flexible and inflexible precipitators to avoid high enlargement costs. Therefore the "first day" efficiencies of the two devices will be approximately the same while the installation costs of the equivalent size flexible precipitator will be higher because of extra flexible instrumentation costs. Moreover, the flexible precipitator will have a higher average operating efficiency and consequently higher operating costs. Thus, for a given set of S1 and S2 enforcement parameters (and specifically a relatively tight compliance test standard) a cost minimizing firm would pick an inflexible precipitator of lower average operating efficiency but the same first day efficiency.

Similar analysis has been carried out for scenarios S3, S4, S5 and S6. The results are summarized in Figure 12. Feasible enforcement policies lie in the inclusive area between the dashed perpendiculars and the line CB extended beyond B. Emission taxes below $5 per ton are likely to be less than the minimum average cost of pollution control and therefore they probably would not impact pollution control effort. A compliance test of less than .02 lbs. per million B.t.u. is a very strict standard which would probably encourage legal challenges by affected industries. FF is the locus of compliance standards and emission taxes for which total flexible and inflexible precipitator out-of-pocket costs for a 1300 megawatt plant are equal. This locus or policy frontier is determined by setting 1300 megawatt costs as a function of enforcement policy parameters from scenarios S3 and S4, equal to each other. In the shaded area to the left of FF, inflexible technology is cheaper. To the right, flexible is less costly. BC is the locus of compliance test standards and emission taxes using compliance-test-with-emission-tax enforcement and emission-tax-only enforcement for which precipitator efficiency is equal in a comparison of these two alternative enforcement schemes. It is determined by setting 1300 megawatt efficiencies as a function of enforcement policy parameters from scenarios S4 and S6 equal to each other. The curve labeled 99.54 is the 99.54% or "law abiding" iso-efficiency curve for a flexible precipitator under emission tax enforcement. The curve labeled 99.67 is a similar curve under compliance-test-tax enforcement where inflexible technology is cheaper. The point labeled G is the compliance test standard and emission tax combination where total expected costs to the firm for a 99.54% efficient precipitator are equal to tax-only enforcement at H.

Figure 12*
Enforcement by Compliance Test and
Emission Tax
1300 Megawatt Plant
(N=3,MD=0,R=1.1V)**



*Similar tradeoffs occur at other plant sizes.
**An average of three stack samples (N=3), no limits on the number of successive compliance tests (MD=0), and an intermediate level for the flue gas flow rate (1.1V) are representative of current enforcement practice.

To the left of G on the 99.54% iso-efficiency curve, the test-tax policy combinations result in smaller costs to the firm while to the right of G they are more expensive than tax-only enforcement (indicated by point H). At point I, compliance standard of .1 (the current EPA standard) combined with an emission tax of $56/ton would induce a cost minimizing firm to pick a "law-abiding" 99.54% efficient precipitator. However, note that an emission tax alone of the same amount would produce the same level of control at less expected cost to the firm. Point K is the least cost point for the firm under compliance-test-tax enforcement.

Figure 12 also indicates that flexible technology enjoys a relative policy advantage under emission tax enforcement. This occurs because increased flexibility allows the firm, for a given precipitator size, to reduce total emission taxes. Loosely speaking, flexible technology will cost less than inflexible as long as this emission tax savings (offset by some additional fly ash disposal costs) exceeds the additional flexible instrumentation costs. This may, of course, not occur if the emission tax rate is relatively small or if the compliance test standard is relatively tight. In these cases enlargement costs dominate technology selection and inflexible technology clearly has a cost advantage over flexible technology.

Enforcement Policy and Technology Development. The model contains two "types" (really degrees) of precipitator technology, labeled, for convenience flexible and inflexible. These particular variants were modeled because they are feasible choices in today's technology choice set. Over time though, one would expect that precipitators even more efficiency-flexible than these could be developed. This raises an important issue, namely, do different enforcement schemes either encourage or discourage the development and adoption of efficiency-enhancing technology?

The answer is that emission tax enforcement schemes encourage such developments while enforcement by compliance test and opacity standard discourages them. We proceed now to investigate the reasons for this. It is assumed throughout this discussion that everything except operating flexibility remains constant including, most particularly, the installed instrumentation costs associated with flexibility.

Figure 13a shows that increasing flexibility reduces emission taxes from an amount proportional to area ABCD to an amount proportional to area AFCD for a given precipitator size. Collected fly ash disposal costs are, in turn, increased in proportion to area ABF. However, the net outcome is usually a reduction in out-of-pocket costs to the firm. Under compliance-test-emission-tax enforcement of environmental standards, increased flexibility may also allow the firm to install a smaller precipitator since the net savings in emission taxes and collected fly ash disposal costs can be traded off against decreased original size costs and increased enlargement costs. Thus under emission tax enforcement of environmental standards, the firm can reduce its costs by adopting technology of greater and greater flexibility. Thus, it will pay them (or their suppliers) to expend resources to develop more flexible technologies.

Assume now that Figure 13a is for enforcement by compliance test and opacity standard. Assume also that the compliance test is relatively tight and that the firm may choose operating curve AB or AF. AF, or a flexible operating curve, would (in addition to instrumentation costs) increase collected fly ash disposal costs in proportion to area ABF. Thus out-of-pocket costs and average collection efficiency for the firm would rise and consequently cost-minimizing firms would not opt for flexible technology.

On the other hand, if the compliance test is lax relative to the opacity standard the firm may be able to choose a flexible operating curve like GB. This reduces its fly ash disposal costs costs and its installation costs by trading off smaller original-size costs against larger enlargement costs. Hence when the compliance test standard is relatively lax, cost minimizing firms may opt for flexible technology. As shown by Figure 13b development of new more flexible technologies

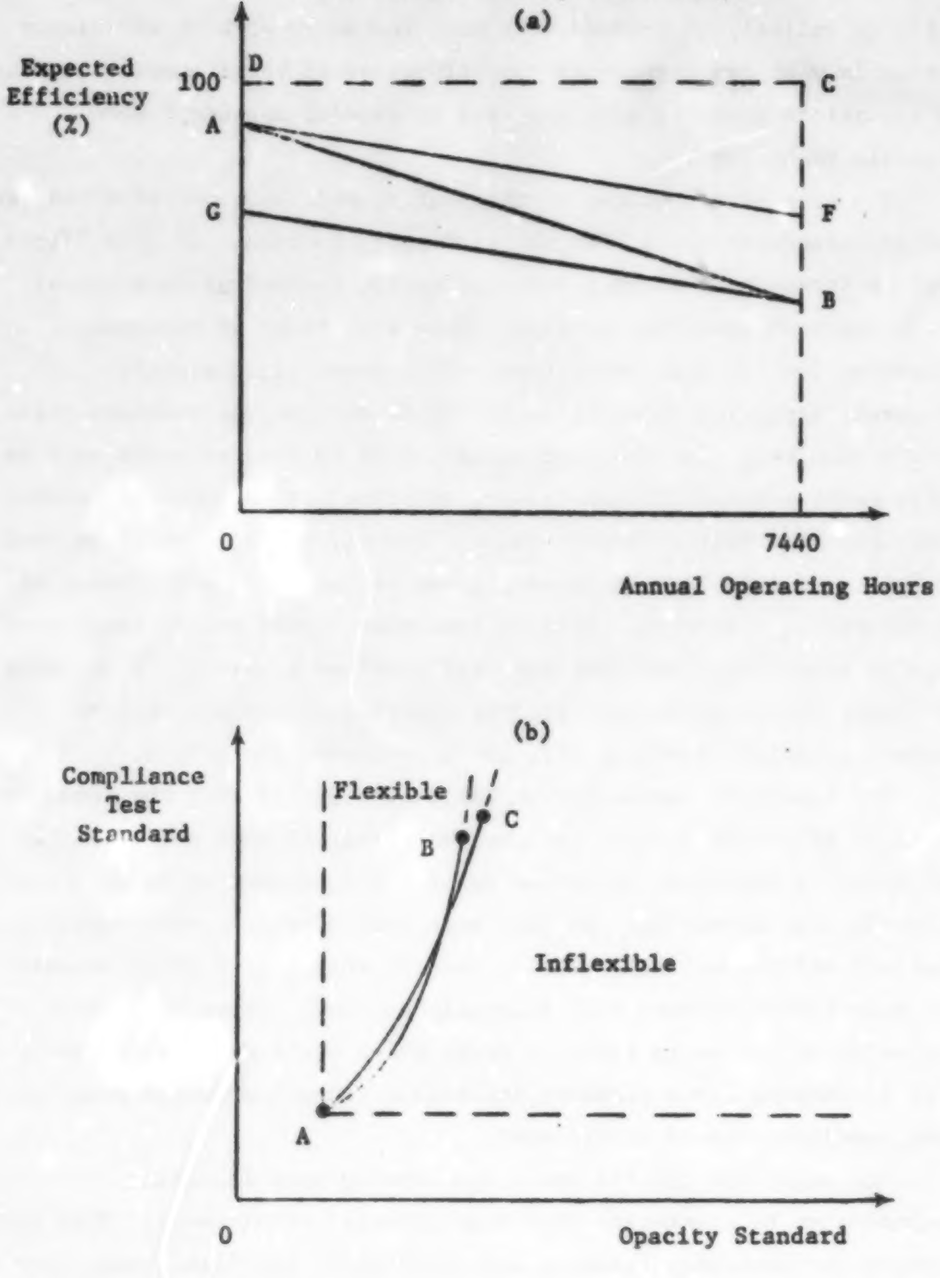


Figure 13

Technology-Cost Tradeoffs
(Current Enforcement Practice)

would shift the equal cost technology locus from AB to AC. But since collection efficiency increases in the southwest direction such a shift is unlikely to produce very many instances at high efficiency standards when compliance-test-opacity-standard enforcement will lead to situations where it pays the firm to develop and adopt more flexible technology.

The crux of the matter is that enforcement by compliance test and opacity standards tends, for the most part, to encourage good "first day" performance by firms. Hence, flexible technology development which improves over-the-operating-cycle efficiency is not cost effective for the firm under these enforcement circumstances. Moreover, improving flexibility generally shrinks the relevant policy area within which flexible technology would be adopted under such an enforcement scheme. In comparison, emission tax enforcement rewards over-the-operating-cycle performance. Hence, costs to the firm tend to fall as flexibility increases, given emission tax enforcement of environmental standards. This is true over a wide policy range even when emission taxes are combined with compliance tests. Or in terms of Figure 12, gains in precipitator flexibility would cause the technology policy frontier, FF, to shift toward the origin.

The important conclusion of the discussion is that the resource costs of pollution control fall as technology is made more flexible and so it is important to devise enforcement schemes which encourage firms in this direction. We have seen that compliance-test-opacity-standard enforcement will usually fail in this regard while emission tax enforcement schemes will generally succeed. Later we provide estimates of the extra resource costs which would occur as a result of cost minimizing firms choosing inflexible technology under compliance-test-opacity-standard enforcement.

One might ask why EPA could not develop more flexible technologies to counteract this bias in legal enforcement. They could perform the necessary research and development but firms would have no incentive to adopt this new more expensive (in out-of-pocket costs) technology unless policy parameters were adjusted to fall to the left of the new AC curve which would result from the developed technology.

SECTION VI

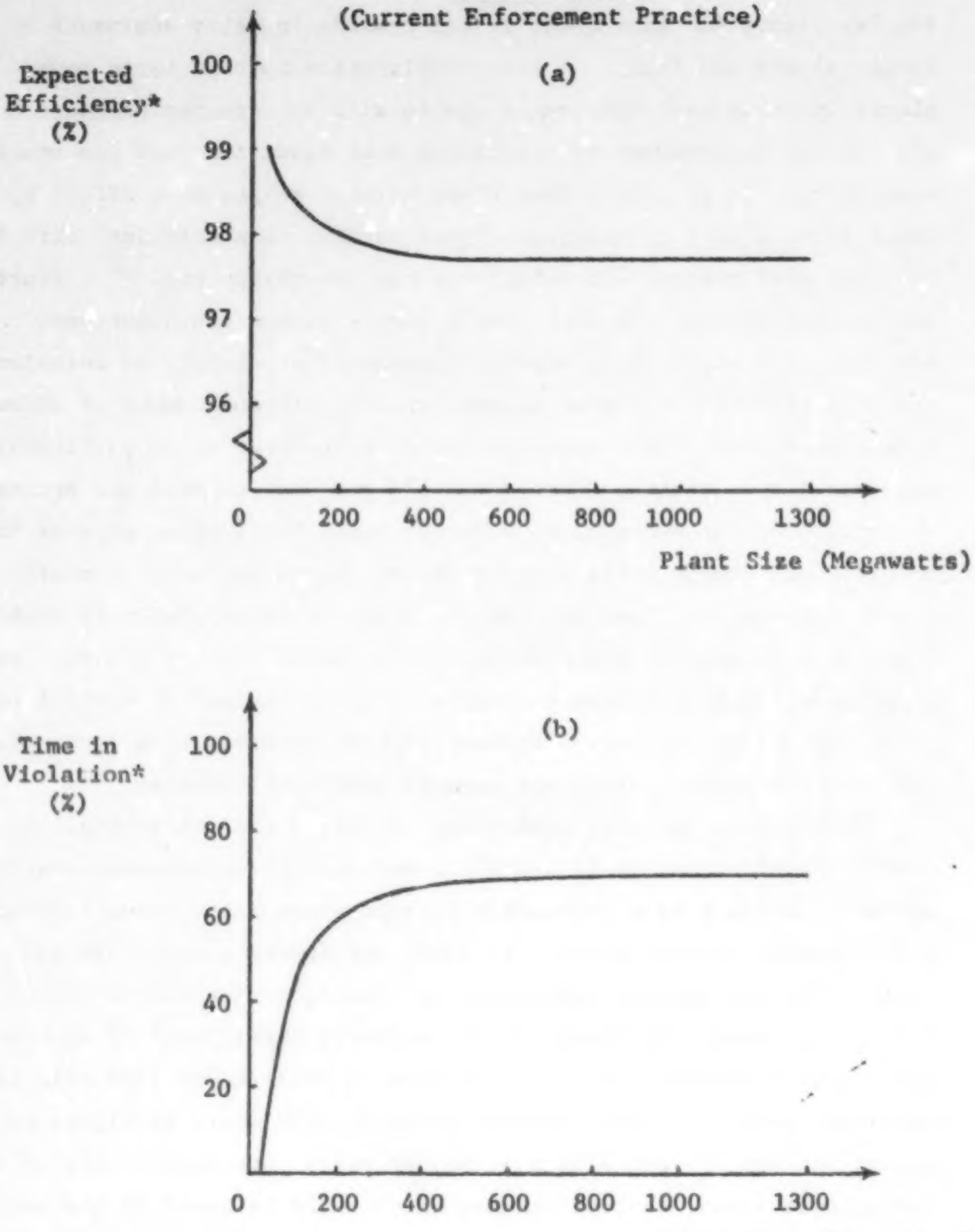
POLICY RECOMMENDATIONS

Current EPA Policy. At this point we can analyze current EPA policy in greater detail. We have already seen that under current enforcement practice a 1300 megawatt plant would control fly ash at approximately the 97.7% efficiency level and choose inflexible precipitator technology. Using our regression results we have also computed collection efficiencies for other plant sizes. These results, shown in Figure 14a, indicate that smaller plants, for the same set of current practice enforcement policies would control at progressively higher efficiencies. The different performance at different plant sizes is due mainly to the existence of economies of scale. Figure 14b converts these efficiencies to time-in-violation of the federal fly ash standard.[21/] In general, under current EPA policy all plants choose inflexible precipitator technology, small plants control at higher efficiencies than do large plants even though large plants have smaller marginal costs of control and significant economies of scale, and all but small plants will be violating the federal fly ash standard for considerable amounts of time.

There are several implications of the differential impact by plant size. One is that it is inefficient and hence undesirable to have small plants with their higher marginal costs controlling fly ash at relatively high levels (assuming equal marginal benefits of control at all plant sizes).[22/] A second implication arises with respect to industry structure and industry competitiveness. In the electric power industry, installation of larger power plants would be encouraged by legal enforcement (compliance tests and opacity standards). Competitiveness, on the other hand, would probably not be affected; this industry is a "natural" monopoly with regulated prices; increased costs would merely be passed on to consumers. Since our analysis has general applicability, it is likely that such differential impacts will also arise in other industries as legal enforcement of pollution control is undertaken. Here smaller plants

Figure 14

Control Effort
(Current Enforcement Practice)



*Performance during base load years, normal load conditions.

will be at a definite disadvantage. When pollution control costs are substantial this could result in the more frequent closing down of smaller plants and subsequent trends towards industry dominance by larger plants and firms. A third implication is that large power plants in comparison with small plants will put greater pressure on EPA for lax enforcement of compliance test conditions and lax stack monitoring. It is likely that there will be substantial effort by large power plants to cultivate "good working relationships" with EPA. The financial rewards for doing this can be substantial.[23/] A fourth implication is that the bias toward larger plants could increase damages. The standard is stated in terms of a quantity of emissions per unit of output. Higher output implies a larger number of allowable tons of emissions, hence a greater concentration of particulates near the larger plant. Since total and marginal damages are probably a function of concentrations, a larger plant would cause greater total and marginal damage while meeting the standard than would a small plant, cet. par.. Thus, the bias in favor of large plants is doubly damaging. Because of the reduction in marginal cost of control for large plants and the greater marginal damages implied by control to a given percentage removal, efficient control dictates that large plants control at a higher percentage removal than small plants.

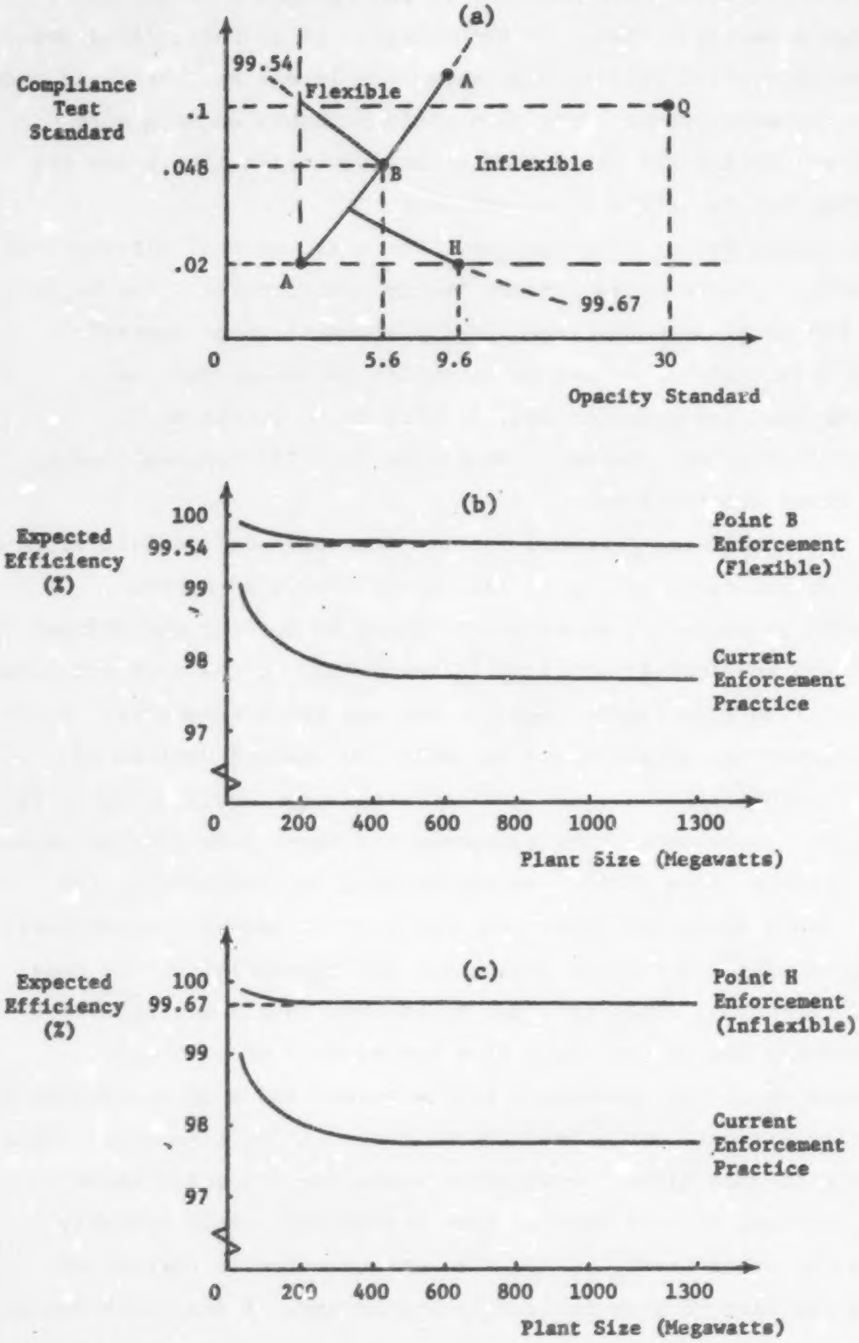
The implications for technology selection are disturbing. At control levels which would prevail under current enforcement practice, our data indicate that inflexible precipitation costs about 1.5% more than flexible precipitation. By 1980, stationary source, air and water pollution control costs will be running at the rate of $5 to $10 billion per year. If standards are enforced legally and if similar technology selection incentives operate in other cases (and this is certainly possible), then control costs by 1980 would be higher by an amount between $75 and $150 million per year. Obversely, this is the approximate annual control expense which could be saved if instead, emission taxes were used to enforce environmental standards at promulgated levels. Moreover, this extra control cost is probably a lower bound estimate. Our analysis of precipitation technology is based upon a marginal change in technology. If in fact, firms had incentive to control pollution at very high levels as they would under emission tax enforcement, they then would probably be much more innovative. This would imply that technology selection losses are larger than $75 to $150 million per year.

Correcting Policy Deficiencies. There are several alternatives for potentially correcting current policy deficiencies. One is to tighten the compliance test and opacity standard under current practice enforcement, another is to switch to enforcement by compliance test and emission tax, a third is to switch to emission-tax-only enforcement. We now explore the implications of each of these alternatives.

At the compliance test and opacity standards to the left of point B on the 99.54% curve in Figure 15a (a tightening of current enforcement at point Q), power plants would be meeting the federal fly ash standard and installing *flexible* technology of the type simulated in our model.[24/] This policy however, has two major drawbacks. Firms would probably not be given the incentive to install devices of greater flexibility (i.e., new devices even more flexible than those now modeled) since under this enforcement scheme, such devices would tend to increase firm costs. An improvement in flexibility, for example, would shift the equal cost frontier AA toward the northwest (see Figure 13b). Hence the technology now identified in the model as flexible technology would continue to be less costly since point B would probably lie to the right of a new equal cost frontier. Furthermore, both the compliance test standard and most particularly the opacity standard would have to be substantially tightened. This could lead to much higher enforcement costs for the enforcement agency. Picking point H instead (see Figure 15a) would probably reduce enforcement costs but has the very undesirable feature of inducing the firm to pick *inflexible* technology. A desirable feature is that either one of these policies would result in more equal

Figure 15

Effective Legal Enforcement



pollution control effort across plant size (see Figure 15b and 15c). Of course, a complete analysis of firm and control agency costs would be necessary to determine the optimal point in the policy space.

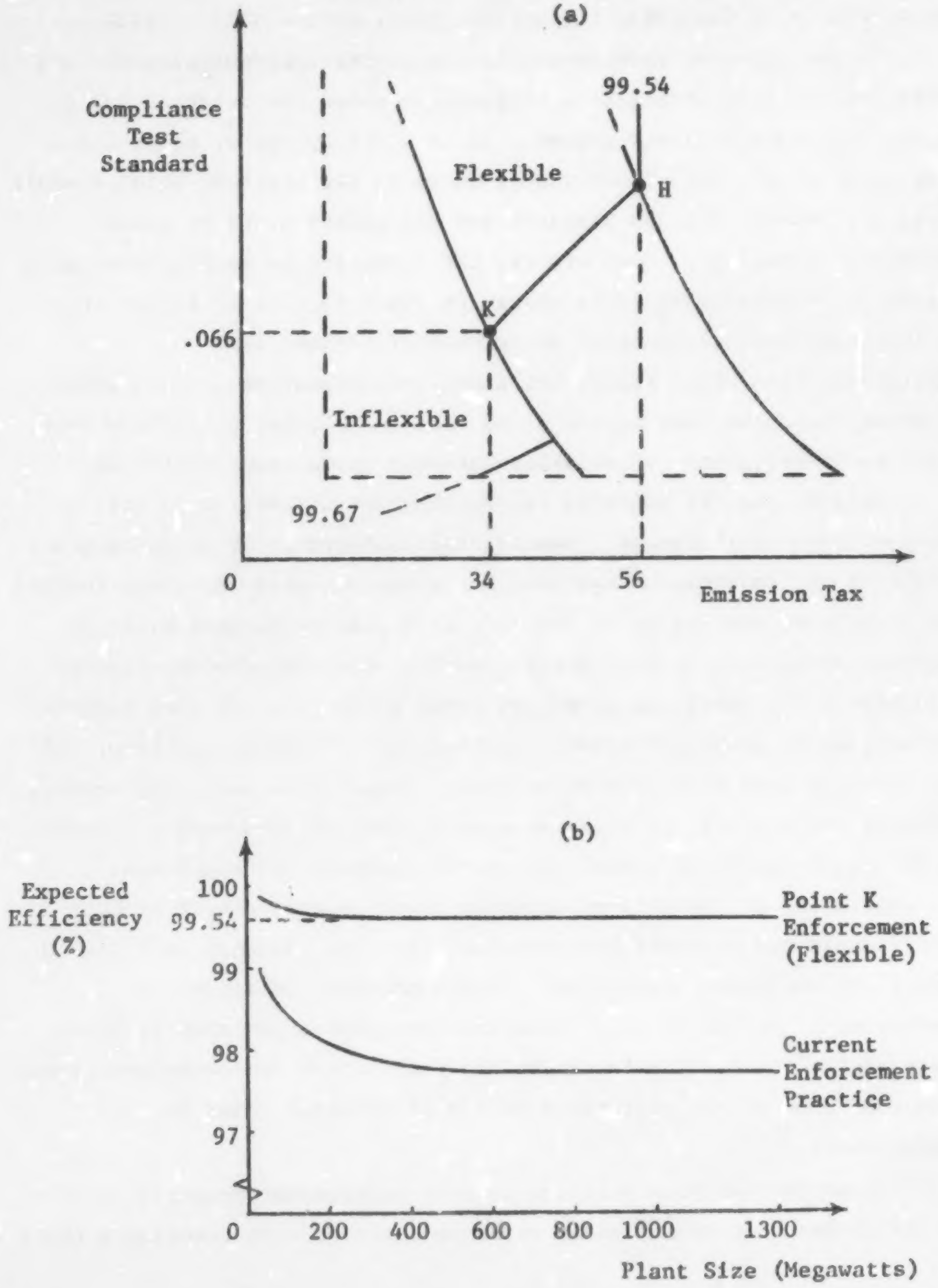
We now consider enforcement by compliance-test-emission-tax and emission-tax-only strategies. Figure 16a shows the relevant policy space and iso-efficiency curves. In this policy space, point K and any point on the 99.54% efficiency curve to the right of point K would meet the federal fly ash standard and all plants would be using flexible technology. Furthermore, the incentive to develop even more flexible technology would be operative since firm costs (given this enforcement scheme) decrease as technology becomes more efficiency-flexible. Figure 16b shows that pollution control effort remains about the same across plant size. A similar pattern evolves from an investigation of emission-tax-only enforcement (point H).

Between the two emission tax enforcement schemes there are, however, some differences. One possible difference is in enforcement costs to the enforcement agency. But since our model does not include such costs we are unable to say what this cost difference might be. Another difference is that compliance-test-emission-tax enforcement can have lower total out-of-pocket costs to the firm so that industry reductions in growth of output, another way to reduce pollution, will be somewhat less with this enforcement scheme. The major difference, however, is probably in acceptability of the two enforcement schemes. Enforcement agency personnel are usually lawyers and engineers. Understanding of the role of emission taxes in enforcement by such individuals has improved but there is still the tendency to cling to legal and technical approaches. Compliance-test-emission-tax enforcement has the obvious "acceptability" advantage that it keeps part of the technical enforcement approach intact and consequently may overcome some of the resistance to use of emission taxes in enforcement.[25/]

In comparison with stricter current enforcement practice, emission tax enforcement alone or in combination with compliance tests

Figure 16

Effective Emission Tax Enforcement



seems to be a better method of effective enforcement. Most importantly, emission tax enforcement provides incentives toward the adoption of resource saving flexible technology. Indeed savings in control cost due to emission-tax-induced accelerated technology development are likely to be very large. Furthermore, since emission charges are immediate there is little the firm can do to avoid compliance. There is, however, one sense in which firms could avoid or delay compliance under emission tax enforcement. This is by initial challenges to emission tax legislation. Our results indicate that effective emission tax enforcement can raise out-of-pocket costs to the firm by as much as 25% above costs incurred under current-practice enforcement. Thus there are substantial cost savings to firms from preventing emission tax enforcement of pollution standards. An implication is that substantial resources may have to be devoted to passage and legal defense of emission tax legislation.

Policing of stack monitoring is the one activity to which a pollution control agency must devote substantial resources under emission tax enforcement. Cost minimizing firms will achieve high collection levels only if full and proper emissions charges are levied. Honest and hence carefully policed, stack monitoring is a necessary condition for this.

SECTION VII

INTERPRETING THE RESULTS

This study has attempted to produce a generalized theory of enforcement and a specific application. As with any such endeavor, simplifying assumptions have had to be made to make the problem tractable. This limits our ability to interpret the simulation results and generalize them into recommended policies for EPA. In this section we explore the limits to our study, discuss the generality of our results, and suggest further research needed to solve unanswered questions.

Qualifications. A number of simplifications have been made in our model which are worth mentioning at this point. The important aspect is the extent and direction of their impact on enforcement policy characteristics and comparisons.

Recall that the model assumes firms attempt to minimize expected costs. But if in actual fact firms are risk averse, they may tend to control at somewhat higher levels than the model predicts. For example, a firm facing a very large fine for violating the opacity standard may "play it safe" and pick a rather large precipitator to avoid the remote possibility of such a heavy penalty even though the expected fine is relatively small. The same thing can be said about firm reaction to failing the compliance test if enlargement costs are relatively large. The exact opposite behavior occurs of course, if firms are risk seeking. However, it should be pointed out that in the actual runs of the simulation model (expected cost minimizing behavior) firms almost never selected precipitators which violated the opacity standard. Hence in our specific application it is mainly reaction to the compliance test which could generate firm behavior different from what we have predicted.

Another important qualification to the model is the absence of firm challenges to enforcement. For example, some runs of the simulation model indicated that for given policy parameters, firms would control at relatively high efficiency levels. In actual fact when firms are faced with such situations they may use legal and political resources to "purchase" lax enforcement. The reason is that control costs increase at an increasing rate and consequently such countervailing expenditures look increasingly attractive to the firm. Behavior of this sort which is not now included in the model would generate lower control levels than predicted.

On balance, we think that the simulation model probably overstates firm pollution control effort especially for large plants. However, this qualification does not alter relative comparisons between the alternative enforcement schemes. These important and useful results remain intact.

Recall also that the model uses Monte Carlo selection of costing and engineering parameters from specified distributions to compute costs. This procedure, designed to capture circumstantial and geographic variation in costing conditions, produces a distribution of results for each set of simulated enforcement policy parameters. By comparing distributions it is possible to determine the frequency of deviation from the model's expected results. Important considerations here are technology selection and relative rankings of firm and resource costs under the different sets of enforcement policies. In general, the model is very robust. There are few cases--5% at the most--when specific parameter selections produce results qualitatively different than the reported expected results.

In addition the Monte Carlo distributions show that variation in control effort is relatively small. Roughly speaking, about 97.5% of the down-side variation in collection efficiency for a given set of enforcement policy parameters is less than one-half of a percentage point. Up-side variation at the 97.5% confidence level is covered by an even narrower range especially at high efficiency levels where distributions are pushed up against 100% efficiency.

Generalizing the Results. Many of the results of our theoretical and empirical analyses are general in character. For example, we would expect that differing combinations of compliance test standards and operating emission standards could yield identical control levels whether we are analyzing fly ash control or automotive emission controls. Likewise, we would expect the technology selection reversal phenomenon to occur in other control situations as well. However, our model and its application does not necessarily imply that these results will occur in the same relevant policy space. Nor can we imply that one form of implementation and enforcement is universally better than another. There most certainly are cases where the technological problems of more-or-less continuous monitoring generally associated with emission tax enforcement would be prohibitively costly and a legal enforcement scheme would be optimal. In the case we analyze we strongly suspect (but cannot prove without additional research) than an effluent fee system is preferable. However, this is almost the ideal case. Monitoring is easy and available. Control technology is developed and well understood. In many other cases this will not be so. Each case will have to be analyzed individually to determine the correct implementation and enforcement technique and the correct levels for the relevant policy parameters.

Additional Research. Our model, as indicated earlier, is incomplete. We have not attempted to simulate enforcement agency costs and behavior. This is the major missing cost link in our analysis. Consequently, we cannot yet determine total marginal costs, that is the least-cost sum of firm marginal control costs, firm marginal management costs, and enforcement agency marginal management costs.

Completing the cost analysis, however, is a straightforward conceptual problem although one which will probably require extensive empirical analysis. Conceptually one would proceed by integrating enforcement agency cost and behavioral equations (all as functions of enforcement policy parameters) into the existing simulation model. Least cost functions could then be determined, as before, by running the model for a variety of enforcement policy sets. Summarization would be accomplished through regression analysis on only the optimum envelope points. In effect, this would estimate reduced form behavioral and cost equations (as a function of enforcement policy parameters) which would reflect the simultaneous minimization of firm control and management costs and enforcement agency management costs. In turn, these equations would allow comparison of marginal and total conditions for alternative enforcement schemes. The final result would be specification of a complete cost minimizing enforcement policy. This, after all, is the core problem of enforcement economics.

FOOTNOTES

1. Other possible control instruments such as subsidies and marketable permits have been neglected in this study.

2. Anderson and Crocker (1971) suggest that these issues are of vital importance in control instrument decisions but do not cite any literature which explores their effects on control.

3. See Watson (1972).

4. See Becker (1968) who suggests a similar but not quite correct point.

5. Becker (1968, p. 199) has noted that: "fines should exceed the harm done if the probability of conviction were less than unity. The possibility of avoiding conviction is the intellectual justification of punative, such as triple, damages against those convicted." Since it is obvious from past experience that polluters are not always convicted, penalties greater than damages and enforcement costs may be justified.

6. While our model does not specifically consider the tradeoffs involved in the interrelationships between control costs and total product output of the firm, the conclusions reached here do hold in the general case. For a model which relates pollution control costs to the optimal output of the firm see Fan and Froehlich (1972).

7. This objective function can easily be translated into Becker's supply of offenses function. However, it is stated in stochastic form rather than deterministic form since many of the terms are stochastic in nature. The first derivative of this function represents the value to the firm of a violation and hence under perfectly competitive conditions the opportunity cost to society of pollution control.

8. Stigler (1970, p. 528) argues strongly for a variable penalty. He concludes that "marginal costs are necessary to marginal deterrence." Thus, penalties such as cases 3 and 4 are to be preferred.

9. For a discussion of the use of reliability in standards see Blumstein, et al, (1972).

10. Tittle (1969) has shown that greater certainty of punishment for a crime is associated statistically with lower offense rates.

11. It has another option, to shift to an alternative enforcement scheme. This may be preferable since in the current legal enforcement scheme non-compliance is "... enforced by criminal process, probably the most cumbersome coercive tool we have. The violator is protected by all the constitutional protections which apply to any criminal trial. He can demand a trial by jury and unanimous verdict (and this against the heavy burden of proof faced by the prosecution)." (Krier, 1970, p. 5-29).

12. Penalty costs in this case are the increased costs of producing the power from alternative sources and the interest on investment in the plant during the six months that would be required to complete the expansion.

13. Two very computationally complicated variants of this model were investigated. One was least cost selection of load shedding or fines when the opacity standard was violated. Another was least cost selection of serial enlargement or a single stage enlargement. In a sensitivity analysis, both variants in combination produced results approximately equal to those of the simpler basic model.

14. In a few cases 1000 iteration, Monte Carlo simulations were completed and compared to the results of the 100 iteration runs. In each case the results were identical to six or more decimal places.

15. The shifts in the power function are due to the central limit theorem.

16. N was included in equations (13) and (14) only when it was a significant determinant of cost and when N was not intercorrelated with E. This occurred mostly for the 25 megawatt plants.

17. One might logically ask why a firm would bother to operate the device if PC actually were zero. We assume it operates so as to avoid a flagrant violation of the law and the political and social costs of doing so. However, it could be the case that the firm would stop operating the device when PC=0.

18. The relevant economic costs for resource management are resource costs; fines and taxes paid by firms are transfer payments which should not influence resource allocation decisions.

19. Cost differences of about the same relative magnitude occur at other plant sizes. Note that we have assumed that record keeping and fee paying costs do not vary with the removal rate.

20. The enforced opacity standard is likely to be 30% or higher, rather than the promulgated 20%. In the past courts have levied fines only when violations were considerably greater than the relevant standards and when firms were uncooperative and incalcitrant.

21. Time in violation (base load years, normal load conditions) is computed using the following equations:

$$IT = \begin{array}{l} 100,\ AE<96.4 \\ SQRT[(99 - AE)/.0026],\ 96.4 \le AE \le 99 \\ 0,\ AE>99 \end{array}$$

$$FT = \begin{array}{l} 100,\ AE<97.7 \\ (98.8 - AE)/.011 \quad 97.7 \le AE \le 98.8 \\ 0,\ AE>98.8 \end{array}$$

where IT=inflexible precipitator time-in-violation (base load years, normal load conditions)

FT=flexible precipitator time-in-violation (base load years, normal load conditions)

AE=average expected efficiency (base load years, normal load conditions)

22. Becker (1968, p. 189 and 196) derived a similar result on theoretical grounds. He argues that penalties (or standards) should be less for smaller violators (plants) and that high income firms should be prosecuted more thoroughly rather than less thoroughly as we have found in our analysis.

23. This implies that the curve in Figure 14b represents a lower bound estimate to the actual time in violation.

24. At point B, the firm would be indifferent between technologies.

25. It also reduces the power lost by the control agency bureaucrats thus further increasing its acceptability to them (see Section II).

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MATHEMATICAL APPENDIX

Figures 2 and 5 show the efficiencies, costs and probabilities which enter the simulation model. Equations and parameter values for these are presented below. Symbols are defined in Table A.1.

Expected Precipitator Efficiency. The following equation (Watson (1970 and (1973b))) is used to compute expected precipitator efficiency (EPE):

$$\text{(A.1)} \quad EPE = \text{Expectation } \{100 \cdot [1-\exp(-z \cdot \exp u)]\}$$

$$\text{where } z = a_0 (A/V)^{a1} (KW/V)^{a2} (S/Ah)^{a3} (a_4)^{MF}$$

$$\text{and } u \text{ is } N(0, \sigma_u^2)$$

Values for parameters a_0 through a_4 and the variance of u are listed in Table 2.A. These have been estimated via regression analysis using cross section data on 37 precipitator systems (Watson (1970)).

Equation A.1 has two key functions in the simulation models. One is to determine expected precipitator efficiency during a compliance test. This establishes the probabilities of pass and fail for each of the precipitator sizes considered in simulating the compliance test. The following Monte Carlo procedure is used (Dienemann (1966)):

1. Designate a value for z.
2. Randomly select a value for u from its distribution.
3. Compute efficiency using equation A.1 (without taking the expectation).
4. Repeat step 2 through 3, j times where $j \geq 3$.
5. Average the computed efficiencies, j in number.
6. Repeat steps 2 through 5, 200 times.

In simulating the compliance test the model considers fourteen different precipitators of increasing size, four different compliance test standards, and four different flue gas flow rates. Some representative probabilities of fail are listed in Tables A.3 through A.6. These values reflect the relationships demonstrated in Figures 7a, 7b and 7c.

The second function of equation A.1 is to determine the days per year when a designated opacity standard is violated (scenarios S1 and S2) and the tons of fly ash discharged per year (scenarios

S3 and S4). Linear operating curves for both flexible and inflexible technology are computed using the following variant of equation A.1:

(A.2) $EPE = \text{Expectation}\ \{100[1-\exp(-z \cdot \exp u)]\}$

where "first day" $z = z$ and

"last day" $z = (.808)^2 z$ (base load years inflexible technology)

or "last day" $z = (.808)^{.6} z$ (base load years flexible technology)

The deterioration factor, .808, is from Greco and Wynot (1971). The exponent 2 for "last day" inflexible efficiency indicates that both available collecting plate and power input deteriorate under inflexible technology. The exponent .6 for "last day" flexible efficiency indicates that power input only deteriorates under flexible technology. Numerical integration is used in the actual computation of expected efficiency. Operating efficiencies for inflexible and flexible precipitators are shown in Tables A.7 and A.8 respectively.

Expected Precipitator Costs. Installed precipitator costs (IPC) discounted over n years at r% are computed using the following equation (Watson (1973b)):

$$(A.3)\quad IPC = 2V(\ln z)^{1/2} \cdot (1/203)^{1/2} \cdot (d\alpha b_1/1.4)^{.7} \cdot \left[\frac{\dfrac{\beta\sum_{t=1}^{n} k_t h_t/(1+r)^t + d\alpha c_1}{\xi_{T-R}}}{.6}\right]^{.3} \cdot (S/Ah)^{-.11} + d\alpha(b_0 + c_0 EBS) + 200\ MW$$

The term 200MW is the discounted instrumentation cost for flexible technology (scenarios S2, S4, and S6 only).

Compliance tests costs (CTC) are computed as:

(A.4) $CTC = (X1 + S1 \cdot X2)M$

Operating costs are the sum of discounted labor and maintenance costs (DLMC), discounted fan power costs (DFPC), discounted fly ash disposal costs (DFADC), and discounted opacity monitoring costs (DMC).

These are computed using the following equations (Watson (1973)):

$$\text{(A.5)} \quad \text{DLMC} = dm_0 + m_1 \cdot V \cdot \left[\sum_{t=1}^{n} h_t/(1+r)^t \right] \cdot 60$$

$$\text{(A.6)} \quad \text{DFPC} = \sum_{t=1}^{n} \frac{1}{(1+r)^t} \left(\frac{\text{Pressure drop in inches of water} \cdot 5.202 \cdot 1000 \cdot V \cdot h_t \cdot \beta}{44{,}250 \ \text{Fan Efficiency}} \right)$$

$$\text{(A.7)} \quad \text{DFADC} = \sum_{t=1}^{n} \frac{1}{(1+r)^t} \left(\frac{MW \cdot CF \cdot h_t \cdot 1000 \cdot HR}{HC \cdot 2000} \right) \left(\Sigma F_{FA} \cdot Ah \cdot \frac{AE}{100} \right) AC$$

$$\text{(A.8)} \quad \text{DMC} = \text{dMC}$$

The same equations, with some exceptions to be noted, are used to compute enlarged installation and operating costs. One exception is that enlarged costs are keyed to precipitator sizes (certainty size) which have almost no probability of failing the compliance test. For example, Table A.5 shows under test conditions of 1.15V and a compliance test standard of .1 that precipitator 13 (10 stack samples) is of certainty size. When computing enlarged installation and operating costs for smaller precipitators, given a compliance test standard of .1 and flue gas flow rate of 1.15V, the simulation model uses this precipitator size. Similar procedures are followed under other compliance test conditions. A second exception is that enlarged installation costs are premultiplied by a factor, Y3, which adjusts for the extra structural costs required for enlargement. A third exception is that enlarged operating costs include an appropriate compliance test cost for the enlarged precipitator and certain penalty costs. These penalty costs (PC) are estimated as follows:

(A.9) $$PC = (MW \cdot 1000 \cdot Y1 \cdot r/2) + (MW \cdot 1000 \cdot CF \cdot H1 \cdot Y2)$$

The first bracketed term is additional interest on plant investment due to a six month delay for precipitator enlargement. This can be thought of as an opportunity cost to the firm. The second bracketed term is the higher costs of power from an alternative generator during the shutdown-enlargement period. The fourth exception is that the "normal" enlarged operating costs are discounted with a half-year delay to account for operating delays.

The remaining costs are total discounted fines (F) and emission taxes. Fines are computed using the following equation:

(A.10)

$$F = \sum_{t=1}^{n} \text{Day}_t \cdot \text{Fine/Day} \cdot \text{Probability of Conviction}/(1+r)^t$$

Emission taxes are computed using equation A.7 except that average expected efficiency is replaced by one minus average expected efficiency (see Figure 3) and average disposal cost per ton (AC) is replaced by emission tax per ton.

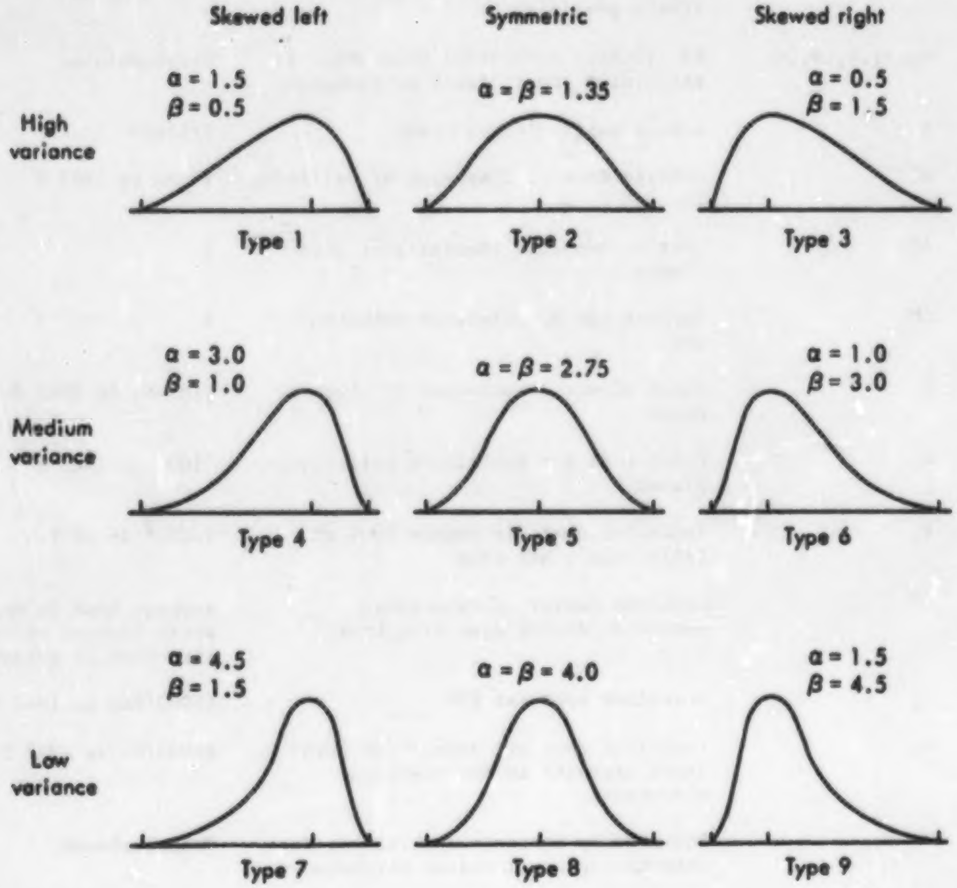
Parameter Values. In computing costs the simulation model randomly selects values from Beta distributions of key costing parameters (Dienemann (1966)). Table A.9 lists their low modal and high values and distribution types. Representative probability density curves for these distributions are shown in Figure A.1.

A number of parameters retain fixed values throughout the simulations. These are listed in Table A.10.

Other values change as the simulation model considers different power plant sizes. These are shown in Table A.11.

Figure A.1

Beta Distribution Shapes Programmed in Monte Carlo Model*



*Taken from Dienemann (1966).

TABLE A.1

NOMENCLATURE

Symbol	Definition	Unit of Measurement
A	Collecting plate area of an electrostatic precipitator	1000's of sq. ft.
a_0, a_1, a_2, a_3, a_4	Empirically determined parameters for explaining precipitator performance	Undimensioned
α	Annual capital charge rate	$/$1000
AC	Average cost of disposing of collected fly ash	$/ton in 1967 $
AE	Average expected precipitator efficiency	%
AH	Percent ash by weight of combusted coal	%
β	Costs of a kilowatt-hour of electric power	$/KW-Hr in 1967 $
b_0	Fixed cost for installing collecting plates	$1000 in 1967 $
b_1	Installed cost per square foot of collecting plate area	$/ft.^{2} in 1967 $
CF	Capacity factor of associated generator during operating hours	Average load in megawatts divided by capacity load in megawatts
c_0	Installed cost per EBS	$1000/EBS in 1967 $
c_1	Installed cost per each KW of power input capacity to the discharge electrodes	$1000/KW in 1967 $
D	Empirically determined parameter for determining precipitator performance	Undimensioned

TABLE A.1 (Continued)

NOMENCLATURE

Symbol	Definition	Unit of Measurement
Day_t	Number of days opacity standard is violated in year t	Days/year t
d	$(1/r)[1-(1+r)^{-n}]$	Undimensioned
E	Weight by fly ash collected divided by weight of fly ash entering an electrostatic precipitator, multiplied by 100	%
ϵ_{T-R}	Average efficiency of the transformer-rectifier sets in a precipitator	Undimensioned
EBS	Electric bus sections in an electrostatic precipitator	The number of EBS's
h_t	Number of coal burning hours of associated boiler in year t	Hours/year t
Hl	Shutdown hours for enlargement	Number of hours
HC	Average heat content of combusted coal	BTU/lb. of coal
HR	Average heat rate of associated generator	BTU/KW-hr.
k_t	Average rate of power capacity utilization in year t	Undimensioned
KW	Power input to the discharge electrodes of an electrostatic precipitator	Kilowatts
m_0	Fixed operating and maintenance cost	1967 $
m_1	Operating and maintenance cost per each cubic foot of flue gas treated	$/ft.^{3} in 1967 $

TABLE A.1 (Continued)

NOMENCLATURE

Symbol	Definition	Unit of Measurement
M	Number of Compliance Tests	Number of tests
MW	Output rating at full capacity of associated generator	Megawatts
MC	Opacity monitoring costs	1967 $/yr.
n	Number of years of operation	Number of years
r	Discount rate	Undimensioned
S	Percent sulfur by weight of combusted coal	%
S1	Number of Compliance Test Stack Samples	Number of samples
EF_{FA}	Fly ash emission factor for combusted coal	Tons of fly ash generated from 1% ash coal per ton of combusted coal
u	Random error term in the regression equation for efficiency	Undimensioned
V	Normal load volumetric flue gas flow rate through a precipitator	1000's of cubic feet/minute
X1	Setup cost for compliance test	1967 $/test
X2	Cost per stack sample (compliance test)	1967 $/sample
Y1	Installed capital cost of an electric generating unit	1967 $/KW
Y2	Penalty cost for alternative power	1967 $/Kwh
Y3	Cost penalty multiplier for precipitator enlargement	Undimensioned

TABLE A.2

ELECTROSTATIC PRECIPITATION PARAMETERS

Parameter	Estimated Value	Standard Error
a_0	Exp(5.06) = 157.6	.43
a_1	1.4	.165
a_2	.6	.1
a_3	.22	.0975
a_4	Exp(.252) = 1.29	.1477
σ_u^2	.12	

TABLE A.3

COMPLIANCE TEST FAILURE PROBABILITIES

(R = 1.15V, Compliance Test Standard = .04)

Sample Size	Precipitator Number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	1.000	1.000	1.000	1.000	1.000	.970	.943	.893	.813	.790	.767	.557	.260	.113
5	1.000	1.000	1.000	1.000	1.000	.993	.990	.947	.913	.907	.873	.617	.233	.087
10	1.000	1.000	1.000	1.000	1.000	1.000	.997	.990	.987	.977	.953	.723	.217	.057
15	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.997	.997	.987	.780	.200	.013
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.997	.833	.187	.003
25	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.880	.173	.010
30	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.913	.157	.007
35	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.917	.140	.003
40	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.937	.130	.000
45	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.943	.110	.000
50	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.960	.097	.000

TABLE A.4

COMPLIANCE TEST FAILURE PROBABILITIES

(R = 1.1V, Compliance Test Standard = .04)

Sample Size	Precipitator Number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	1.000	1.000	1.000	1.000	.993	.920	.883	.797	.737	.690	.660	.380	.157	.043
5	1.000	1.000	1.000	1.000	1.000	.983	.953	.877	.820	.810	.743	.450	.100	.033
10	1.000	1.000	1.000	1.000	1.000	1.000	.990	.977	.937	.903	.860	.493	.083	.003
15	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.993	.960	.977	.930	.493	.037	.000
20	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.990	.983	.957	.567	.017	.000
25	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.987	.997	.983	.573	.020	.000
30	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.990	.573	.013	.000
35	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.997	.993	.603	.007	.000
40	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.997	.607	.003	.000
45	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.613	.000	.000
50	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.597	.000	.000

TABLE A.5

COMPLIANCE TEST FAILURE PROBABILITIES

(R = 1.15V, Compliance Test Standard = .1)

Sample Size	Precipitator Number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	1.000	1.000	.997	.987	.973	.823	.767	.633	.527	.483	.410	.207	.047	.000
5	1.000	1.000	1.000	1.000	.993	.910	.830	.703	.593	.550	.473	.160	.017	.003
10	1.000	1.000	1.000	1.000	1.000	.983	.930	.840	.670	.620	.443	.090	.000	.000
15	1.000	1.000	1.000	1.000	1.000	.993	.960	.890	.747	.650	.460	.060	.000	.000
20	1.000	1.000	1.000	1.000	1.000	.997	.987	.937	.773	.683	.467	.033	.000	.000
25	1.000	1.000	1.000	1.000	1.000	1.000	.993	.950	.800	.717	.470	.023	.000	.000
30	1.000	1.000	1.000	1.000	1.000	1.000	.990	.960	.823	.730	.487	.017	.000	.000
35	1.000	1.000	1.000	1.000	1.000	1.000	.993	.970	.820	.760	.503	.010	.000	.000
40	1.000	1.000	1.000	1.000	1.000	1.000	.997	.993	.850	.790	.510	.010	.000	.000
45	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.993	.873	.790	.507	.003	.000	.000
50	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.990	.877	.803	.513	.001	.000	.000

TABLE A.6

COMPLIANCE TEST FAILURE PROBABILITIES

(R = 1.1V, Compliance Test Standard = .1)

Sample Size	Precipitator Number													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	1.000	1.000	.997	.970	.917	.710	.590	.510	.393	.350	.287	.100	.020	.000
5	1.000	1.000	1.000	1.000	.977	.823	.647	.553	.433	.370	.317	.050	.000	.000
10	1.000	1.000	1.000	1.000	1.000	.920	.743	.620	.380	.333	.200	.020	.000	.000
15	1.000	1.000	1.000	1.000	1.000	.967	.790	.660	.410	.303	.140	.000	.000	.000
20	1.000	1.000	1.000	1.000	1.000	.983	.860	.697	.400	.287	.103	.000	.000	.000
25	1.000	1.000	1.000	1.000	1.000	1.000	.883	.747	.417	.283	.110	.003	.000	.000
30	1.000	1.000	1.000	1.000	1.000	1.000	.913	.740	.387	.273	.110	.000	.000	.000
35	1.000	1.000	1.000	1.000	1.000	1.000	.927	.727	.377	.293	.110	.000	.000	.000
40	1.000	1.000	1.000	1.000	1.000	1.000	.930	.770	.390	.303	.087	.000	.000	.000
45	1.000	1.000	1.000	1.000	1.000	1.000	.953	.810	.400	.250	.070	.000	.000	.000
50	1.000	1.000	1.000	1.000	1.000	1.000	.960	.780	.370	.253	.067	.000	.000	.000

TABLE A.7

PRECIPITATOR CHARACTERISTICS
(Inflexible Technology)

Precipitator	z	First Day* Efficiency (%)	Last Day* Efficiency (%)	Average* Efficiency (%)	% of Time in Violation of Standard* (%)
1	2.756	91.96	82.12	87.04	100
2	2.998	93.37	84.39	88.88	100
3	3.289	94.72	86.74	90.73	100
4	3.654	96	89.14	92.57	100
5	4.134	97.19	91.59	94.39	100
6	4.836	98.3	94.15	96.23	100
7	5.347	98.8	95.47	97.14	86
8	5.598	98.98	96	97.49	78
9	5.974	99.21	96.67	97.94	65
10	6.094	99.27	96.86	98.07	61
11	6.437	99.41	97.33	98.37	48
12	7.444	99.69	98.33	99.01	0
13	8.861	99.86	99.1	99.48	0
14	9.859	99.92	99.41	99.67	0

*During base load years, normal load conditions

TABLE A.8

PRECIPITATOR CHARACTERISTICS
(Flexible Technology)

Precipitator	z* (IV)	First Day Efficiency* (%)	Last Day Efficiency* (%)	Average Efficiency* (%)	% of Time in Violation of Standard* (%)
1	2.756	91.96	89.47	90.72	100
2	2.998	93.37	91.16	92.27	100
3	3.289	94.72	92.80	93.76	100
4	3.654	96.00	94.40	95.20	100
5	4.134	97.19	95.95	96.57	100
6	4.836	98.30	97.43	97.87	100
7	5.347	98.80	98.14	98.47	29
8	5.598	98.98	98.40	98.69	0
9	5.974	99.21	98.72	98.97	0
10	6.094	99.27	98.81	99.04	0
11	6.437	99.41	99.03	99.22	0
12	7.444	99.69	99.46	99.58	0
13	8.861	99.86	99.75	99.81	0
14	9.859	99,92	99.85	99.89	0

*During base load years, normal load conditions

TABLE A.9

CHARACTERISTICS OF COST PARAMETER DISTRIBUTIONS*

Cost Parameter**	Low Value	Modal Value	High Value	Distribution Type
α	80	140	180	7
AC	.5	1	3	3
β	.002	.004	.008	6
b_0	70	180	290	2
b_1	.5	4.7	8.9	2
c_0	7.2	7.6	8.0	8
c_1	.08	.12	.16	8
HR	8,800	9,400	10,000	5
m_0	1,817	2,317	2,817	8
m_1	.000027	.000033	.000039	8
MC	5,000	10,000	30,000	6
r	.05	.09	.13	8
X1	6,000	12,000	24,000	3
X2	500	1,000	2,000	3
Y1	125	165	205	5
Y2	.0005	.001	.004	3
Y3	1	1.2	2	6

* For parameters measured in dollars, low, modal, and high values are in 1967 dollars.

** Characteristics for b_0, b_1, c_0, c_1, m_0, and m_1 are based upon regression analysis (Watson (1970)). Characteristics for α, AC, β, HR, MC, r, X1, X2, and Y1 are representative of known estimates. Characteristics for Y2 and Y3 are based upon engineering judgment.

TABLE A.10

FIXED "COSTING" PARAMETERS*

$$h_t = \begin{cases} 7{,}440 \text{ yrs. } & 1\text{-}12 \\ 5{,}200 \text{ yrs. } & 13\text{-}17 \\ 2{,}160 \text{ yrs. } & 18\text{-}25 \\ 880 \text{ yrs. } & 26\text{-}30 \end{cases}$$

$S^{****} = .5\%$

$Ah = 6\%$

$CF = .9$

$\Sigma F_{FA} = .0085$

$$k_t = {}^{**}\begin{cases} .889 \text{ yrs. } & 1\text{-}12 \\ .8988 \text{ yrs. } & 13\text{-}17 \\ .9634 \text{ yrs. } & 18\text{-}25 \\ .9851 \text{ yrs. } & 26\text{-}30 \end{cases}$$

Fan Efficiency = .6

Pressure Drop = .5

$\xi_{T-R} = .65$

$HC = 8500$

$k_t^{***} = 1$ for all years

$n = 30$

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* Values are representative of known estimates.

** These values are appropriate for inflexible precipitator technology. They reflect negative exponential failure of discharge electrodes.

*** This value is appropriate for flexible precipitator technology. It indicates full utilization of power input to discharge electrodes.

**** This value, representative of a low sulfur western coal and a desulfurized eastern coal, satisfies new source performance standards for sulfur dioxide emissions.

TABLE A.11

REPRESENTATIVE FLUE GAS VOLUMES AND PRECIPITATOR SECTIONALIZATION FOR DIFFERENT SIZED POWER PLANTS

Plant Size (MW)	V* (1000's of Actual Cubic Feet per Minute)	EBS (Electrical Bus Sections)
25	131	4
200	706	6
800	2,173	18
1,300	3,221	36

* Estimated using $V = 9.03\ MW^{.811}((T + 460)/760)^{1.21}$ (Watson (1970) p. 80). It is assumed that flue gas temperature (T) is 340°F.

*U.S. GOVERNMENT PRINTING OFFICE: 1974 546-317/294 1-3